LONDON

CONVR

e Proceedings

13th International Conference on Construction Applications of Virtual Reality

October 30th - 31st 2013, London UK

Editors **Prof Nashwan Dawood**
Dr Mohamad Kassem

www.convr2013.com

ISBN: 978-0-9927161-0-3

Teesside University

uture
present
buildings.
nturies; and
s information
environment is
nportance of the
entity and diversity
will draw particular
specific architectural,
understand and assess the
buildings in order to have a
the available information from
y diverse depending on the specific

CONVR 2013

Proceedings of 13th International Conference on Construction Applications of Virtual Reality

30-31 October 2013, London

Editors

Nashwan Dawood

Teesside University, UK

Mohamad Kassem

Teesside University, UK

ISBN 978-0-9927161-0-3

Published at Teesside University, UK, by Teesside University.

Organizing Committee

Nashwan Dawood (Chair), Teesside University, UK

Mohamad Kassem (Coordinator), Teesside University, UK

Amit Mhalas and Manu Ramegowda (Secretariat staff) Teesside University, UK

Muneeb Dawood and Rajiv Chavada (Webmasters), Teesside University, UK

Michael Crilly (Digital Media), Teesside University, UK

Sue Tindall (Treasurer), Teesside University, UK

June Alderson (Venue and logistics), Teesside University, UK

Gail Johnson (CRM and Registration), Teesside University, UK

Scientific Committee

Mohamad Kassem, Teesside University, UK

Puteri Shireen Jahn Kassim, International Islamic University Malaysia, Malaysia

Farzad Khosrowshahi, Leeds Metropolitan University, UK

Hiam Khoury, American University of Beirut, Lebanon

Christian Koch, Ruhr University, Germany

Tahar Kouider, Robert Gordon University, UK

Tsuneya Kurihara, Central Research Laboratory, Hitachi Ltd., Japan

Richard Laing, Robert Gordon University, UK

Kincho Law, Stanford University, USA

Angela Lee, University of Salford, UK

Ghang Lee, Yonsei University, Korea

Sang Hyun Lee, University of Michigan, Ann-Arbor, USA

Fernanda Leite, The University of Texas at Austin, USA

Ken Yu Lin, University of Washington, USA

Steve Lockley, Northumbria university, UK

Koji Makanae, Miyagi University, Japan

Zaki Mallasi, Effat University, Saudi Arabia

Emmajane Mantle, University of Glamorgan, UK

Katsuhiko Muramoto, Pennsylvania State University, USA

Khalid Naji, Qatar University, Qatar

Andrew Platten, Leeds Metropolitan University, UK

Milan Radosavljevic, Reading University, UK

Abbas Rashidi, Georgia Institute of Technology, USA

Rafael Sacks, Israel Institute of Technology, Israel

Raj Kapur Shah, Liverpool John Moores University, UK

Lucio Soibelman, University of Southern California, USA

Xin Yi Song, Georgia Institute of Technology, USA

Soheil Soubra, CSTB, France

Paul Stephenson, Sheffield Hallam University, UK

Kenichi Sugihara, Gifu-Keizai University, Japan

Georg Suter, Vienna University of Technology, Australia

Joseph Tah, Oxford Brookes University, UK

Ping Bo Tang, Arizona State University, USA

Foreword

We are honored to welcome you to the 13th International Conference on Construction applications of Virtual Reality (CONVR 2013) organized by Teesside University.

CONVR is one of the world-leading conferences in the areas of virtual reality, augmented reality and building information modeling. This year we are welcoming more than 110 participants from 23 countries to discuss and exchange the latest developments and applications of virtual technologies in the Architectural, Engineering, Construction and Operation industry. We have a group of leading keynote speakers from industry and academia who are covering up-to-date hot topics and are enthusiastic to share their knowledge with you. We received 120 papers and after a rigorous review and editing process, we selected 63 excellent papers to be presented in the parallel sessions, covering five thematic research topics: building information modeling, augmented reality and sensing, real-time visualization, simulation and planning.

We are very grateful to our generous sponsors. Our golden sponsors are Autodesk; HOCHTIEF-ViCon; KBR, and Teesside University. Our silver sponsors are: Datum360; Makemedia; Niven Architects; Synchro Software, and the Journal of Engineering. You will have the opportunity to tour sponsor stands and interact with the companies.

Traditionally CONVR participants have been very loyal to the conference over the past 13 editions. This year we are welcoming numerous first timers and we aim to help them make the most of the conference by introducing them to other participants.

Finally our role on the committee is to identify and discuss with you the innovation, best practices, opportunities and challenges experienced by AECO practitioners and ensure that you leave the conference feeling knowledgeable, inspired and full of new ideas and with many new friends.

We are confident that you will enjoy both the conference and the elegant and charming environment of London's city center.

Prof Nashwan Dawood, Chair

Dr Mohamad Kassem, Coordinator

Technology Futures Institute, Teesside University

Sponsors and Supporting Organizations

AUTODESK

HOCHTIEF ViCon

KBR

TECHNOLOGY FUTURES INSTITUTE

Teesside University

Datum360

makemedia

THE JOURNAL OF ENGINEERING
IET Open Access Research

SYNCHRO SOFTWARE

niven architects

Table of Contents

Author index

Z

KEYNOTE SPEECH I

Jeremy Beeton

Title: Delivering London Olympic-Game Capital Project: Lessons Learned

Bio: Jeremy Beeton's experience and knowledge in project management span more than 40 years. He was the Director General London2012 Olympic and Paralympic Games responsible for managing the full budget and delivery for build, event, legacy and government. He was Chair of Olympic Legacy Board, Chair of Olympic Chief Executives group and Major Projects Review Group work for Treasury. Before this, Jeremy was Principal Vice President of Bechtel with operational responsibility for programme management and delivery of civil engineering projects on a worldwide basis project portfolio circa $ 30 bn. He was leading the implementation of sustainable development policies, safety and six Sigma policies. Currently, Jeremy is Director of EPC Global, non-Executive Director of SSE plc and A. Proctor Group, Advisory Board of PricewaterhouseCoopers, Advisory Panel and Consultant to Macquarie, Member of Court at Strathclyde University.

KEYNOTE SPEECH II

Prof. David Philp, Head of BIM Implementation Cabinet Office, London

Title: BIM: UK Government Task Group

Bio: David is currently the head of BIM Implementation at the Cabinet Office's Efficiency and Reform Group, the Head of BIM at Mace and a Professor at Glasgow Caledonian University. He is also chair of the BIM2050 and various BIM4 working groups. David graduated in the early nineties and straight away joined Balfour Beatty as a Graduate Engineer; he advanced through the company becoming Director of Technical Services and latterly BIM programme Director. He still lives in Scotland and his hobbies include photography and collecting air miles.

David's enthusiasm lies in highlighting the potential of new technologies and how we interact with them to bring added value and unlock new ways of working throughout the entire life-cycle. David is passionate about the construction industry and perceives BIM as being a catalyst for reform.

KEYNOTE SPEECH III

Prof. Anthony Steed, Head of VECG at University College London

Title: BEAMING: Asymmetric Telepresence Systems

Abstract: Beaming is the process of virtual teleporting to a destination. Based (loosely) on the idea from Star Trek, a visitor is transported to a destination so that they can interact with other people (locals) there. We achieve this using a combination of high-end virtual reality equipment, robotic platforms and scene reconstruction software.

In the Beaming system we have abandoned a notion that is typical in tele-collaboration: that each party has access to similar equipment and software and thus has equitable access to the shared resources be it a collaborative virtual environment or a video space. While we have made the technology very highly asymmetric, we still want to foster high-quality interaction. The paradigm we have chosen is to completely immerse the visitor in a high-end virtual reality. What they see is a real-time reconstruction of another place (the destination) including people within that space (the locals). In the destination, the locals can see the visitor in a few different modalities: as a robot, as a situated display or through augmented reality. The aim is that the locals should feel that the visitor is with them in the destination and that the visitor should feel as if he or she is in the destination with the locals.

Bio: Anthony is the head of the Virtual Environments and Computer Graphics group in the Department of Computer Science at University College London, UK. He has worked extensively in virtual reality systems, 3D interaction, tele-collaboration, novel interfaces and networking for real-time graphics systems. He is UCL's academic lead on the London Media Technology Campus, a new collaboration between the UCL and BBC.

KEYNOTE SPEECH IV

Prof. R. Raymond Issa, University of Florida

Title: BIM and Visualization: a View from USA

Abstract: Spatial-temporal-constraint problems pervade projects during the construction phase, a better understanding of the construction processes will help contractors solve management problems and will significantly enable them to improve productivity levels. Oftentimes, the contractor's ability to solve problems is hindered by their lack of complete understanding of the dynamic complex spatial constraints (e.g., how construction products are related to one another in particular contextual space) and the temporal constraints (e.g., the dependencies for coordinating subcontractors' processes). The use of BIM to model and simulate the whole construction process in a virtual world has led to enhanced construction productivity.

The use of BIM in clash detection, component modularization, and schedule simulation and the incorporation of Augmented Reality in these models have created an advanced game-like environment that allows contractors to choreograph almost every move they make on the job site. This presentation will look at the latest deployments of tools and techniques to enhance visualization in the AEC industry.

Bio: Raymond is currently the UF Research Foundation and Holland Professor in the University of Florida's Rinker School of Building Construction and Director of the Centre for Advanced Construction Information modeling and the Building Information Modeling (BIM) Visualization Laboratory. He has completed over $7 million in information technology related research and he has served as Chair on over 200 Masters Committees and over 30 Ph.D. Committees, Raymond has also authored over 300 journal and conference proceeding articles and scientific reports.

Raymond has received University, College and School level recognition for excellence in research (UF Research Foundation Professor (2)), teaching, and academic advising (Academic Advisor of the Year; PHD Advisor/Mentor (2)). Raymond also serves on the Board of Directors of various professional organizations, including the National Centre for Construction Education and Research and the International Society for Computing in Civil and Building Engineering (ISCCBE). He has served as chair of the American Society of Civil Engineers (ASCE) Technical Council on Computing and Information Technology and on various other ASCE technical committees. He also serves as an ASCE representative on the Pan American Union of Engineering Societies (UPADI). Raymond was recently awarded the 2012 ASCE Computing in Civil Engineering and elected to the Pan American Engineering Academy.

KEYNOTE SPEECH V

Dr.-Ing. Jan Tulke, Head of Research & Product Development at HOCHTIEF ViCon GmbH

Title: Implementation of BIM in project management

Abstract: Despite the current hype around Building Information Modeling (BIM) a continuous application of Virtual Reality (VR) technologies within the management of construction projects is still relatively new. BIM supporting software tools are mature and widely available on the market but the implementation of BIM on project or company level requires a thorough implementation strategy considering the following five components: people, processes, technology, policies and the ongoing BIM management. In order to reach a deep integration BIM has to be introduced already very early in the project. On use case per use case basis requirements have to be balanced with existing knowledge, end-user usability, technical robustness, immediate benefit, direct and indirect implementation risks as well as initial and recurring investment costs. Critical for the success of a BIM use case is its complete process support. That means BIM is not only a software tool used at a specific time to support or automate a single task. Instead it is a continuous data management method which supports the actors of different use case in terms of more structured, transparent and quicker data editing and data access needed to perform their traditional tasks and responsibilities. Because of the collaborative character of construction projects this requires to orchestrate stakeholders from different organizations with different tools and established working routines. By establishing a BIM management team as well as policies and guidelines designers and construction professionals are released from handling the nuts and bolts of the technical implementation and are guided through the process changes.

Experiences from major international projects in the building and infrastructure sector have shown that a thorough BIM management and a focus on the most valuable use cases within the project boundary conditions are key factors for the success of BIM implementation. The main benefit of BIM is still the quick and comprehensive visualization of complex information in its spatial context. This is not only valid for the 3D geometry itself (e.g. for design coordination) but in particular also for interlinked technical and management data (e.g. specifications, quantities, schedule, costs). This data traditionally is deeply buried in separate data structures such as spreadsheets, specialized expert software or even spread across paper based forms, documents and photos (e.g. sign-off forms, progress reports and non-conformance reports).

Thus the challenge of BIM management is to organize a smooth information flow: With minimum effort data created along the process by various stakeholders has to be collected in a structured way, processed and interlinked automatically in order to be provided to the project team in a way which provides both, condensed management information as well as detailed drill down and search capabilities across all sources. This can only be reached by combination of several existing technologies such as VR, business intelligence, enterprise collaboration, mobile devices and geo information systems.

Bio: Jan is Head of Research & Product Development at HOCHTIEF ViCon GmbH, a consultant company for Building Information Modeling (BIM). The core business of ViCon is BIM Management and the implementation of BIM on project and organization level by guiding changes in all five relevant components: people, processes, policies, technology and BIM management. ViCon supports project owners and contractors with major infrastructure and building projects worldwide, and pushes the advancement of BIM through its participation in international research projects.

Jan graduated civil engineering at TU Berlin with emphasis on computational mechanics and information technology. He started his professional career in the design of infrastructure projects but quickly specialized in the area of Virtual Design and Construction (ViCon). He holds a Ph.D. in construction informatics from Bauhaus University Weimar. As a member of the ENCORD Virtual Construction Platform he has a broad knowledge of current BIM implementation status within many European contractors.

KEYNOTE SPEECH VI

Prof. Xiangyu Wang

Title: BIM Initiative in China

Abstract: More and more countries started to mandate the adoption of Building Information Modeling (BIM) in public projects with certain significance. Although the original concept of BIM was born around two decades ago it has not attracted sufficient attentions for implementation until recently. Particularly in Asia, BIM is becoming more active than before; however, the majority of applications are focused on architecture design and geometric modeling. Construction is an important phase where BIM can exercise its much larger potentials after its prevalent success in the design and engineering stages. For this to happen, BIM must evolve beyond itself to reach the integrated BIM, for example, it needs to acquire information from technologies such as sensor network and feedback decisions and information to site via technologies such as Augmented Reality and ubiquitous computing.

This keynote talk will focus on an angle of the insights of implementing BIM to enhance construction productivity, performance and safety. Practical BIM projects in Asia particularly in China and Australia in which Prof Wang has experienced will be highlighted towards an insightful summary of the state-of-the-art as well as future trends. The cases are from building, infrastructure and oil and gas industries. A cross industry comparison of BIM success and barriers will be discussed in the speech. Critical research issues and future directions will be presented in the talk as well.

Bio: Prof. Xiangyu Wang is holding Curtin-Woodside Chair Professor for Oil, Gas & LNG Construction and Project Management and the Co-Director of Australasian Joint Research Centre for Building Information Modeling (BIM). Professor Wang is an internationally recognized leading researcher in the field of Construction IT, BIM, Lean, Visualization Technologies, Project Management, and Training, having obtained over AUD $ 5 Million research funds and published over 300 peer-reviewed technical papers. He is the Chair of Australian National Committee of International Society in Computing in Civil and Building Engineering. He has presented over 20 keynote speeches at international and industrial conferences on BIM, construction and project management, VR and AR research and practice. He is currently the Editor-in-Chief of Visualization in Engineering which is an international research journal hosted by Springer-Verlag. His work with Woodside Energy Ltd. and other industries, wins numerous awards including the Runner-Up of 2012 Curtin Commercial Innovation Award.

KEYNOTE SPEECH VII

Prof. Dr. Leandro Madrazo

Title: SEMANCO: an open platform to model urban energy systems using semantic technologies

Abstract: The SEMANCO integrated platform (www.semanco-project.eu) provides access to semantically modeled energy related data about cities. It enables an energy model of a city to be developed and includes a set of tools to visualize and analyze a city's energy data. The aim is to help architects, planners, engineers, local administrators, policy makers and citizens to make fully informed decisions about how to reduce carbon emissions in cities. The visualization tools combine interactive 3d models, tables and diagrams to display energy related data. The analysis tools use data mining techniques to enable consultants, policy makers and planners to calculate energy performance indicators. So far, the platform has been applied to three case studies: Manresa in Barcelona, Spain; Copenhagen, Denmark; and Newcastle upon Tyne, UK. The open structure of the platform enables a city's energy model to be enhanced when new tools and/or data become available. This data may be generated by the tools in the platform or come from data sources external to the platform. In this presentation we will show the current state of the platform development including some of the implemented functionalities to visualize and analyze energy related data in cities.

Bio: Leandro Madrazo is a professor at the School of Architecture La Salle, Universitat Ramon Llull, Barcelona, where he has been head of the ARC Architecture Representation Computation research group since its creation in 1999. He graduated in architecture from the Universitat Politècnica de Catalunya in 1984, and studied later as Fulbright scholar in the Master of Architecture programs of Harvard University and at the University of California Los Angeles, where he obtained the Master's degree in 1988. From 1990 to 1999 he carried out his teaching and research work at the Department of Architecture and CAAD at ETH Zürich, completing his Ph.D. programme in 1995. He has participated in several European and nationally funded projects dealing with the development and application of ICT to foster the industrialization of the construction sector and to improve the energy efficiency of buildings and cities. Currently, he is coordinating the research project SEMANCO –Semantic Tools for CO2 Reduction in Urban Planning– funded by the 7th Framework Programme 2011-2014.

KEYNOTE SPEECH VIII

Paul Jonathan Walker

Title: Current and Future Trends of VR Technologies Applied to Construction: a Technology Prospective

Bio: Paul is a Product Manager for Autodesk, in the BIM 360 group. With over a decade of experience in training and evangelizing the benefits of BIM for Construction, Paul is currently focused on cloud and mobile solutions, looking to leverage the latest technologies to simplify processes, and ensure data is securely accessible.

PART I: BIM & VR IN PLANNING AND DESIGN

AUTOMATED SUSTAINABILITY COMPLIANCE CHECKING PROCESS: PROOF OF CONCEPT

Tala Kasim, Hajiang Li, Yacine Rezgui & Tom Beach
School of Engineering, Cardiff University, Cardiff, UK

ABSTRACT: *Building Information Modelling solutions are evolving to achieve effective integration in the construction industry. The emerging approaches of knowledge sharing and data processing push the researchers to re-engineer innovative automated processes for integrated 3D design that complies with regulations and statutory requirements. This paper presents a generic approach for automating BIM compliance checking with standards and best practice with a focus on sustainability related standards. A methodology will be presented to provide a reusable solution for compliance checking within a similar context. The proposed approach is generic in nature thus allowing implementation in different fields of engineering including; electrical engineering, energy, water and electronic engineering. It is anticipated that the findings of this research will promote a fundamentally innovative BIM-based compliance checking for a variety of industry standards. In this approach, the RASE methodology is utilised to extract requirements from sustainability based regulations, with the goal of converting them into compiled coded rules for execution by a rule engine*

KEYWORDS: *BIM; Integrated design; IFC Extension; dynamic sustainability assessment, RASE, Rule engine*

1. INTRODUCTION

Appropriate and efficient methods for designing sustainable and high performance buildings in order to achieve a low carbon footprint are urgently needed by the current construction industry (Everett, Boyle et al. 2012). Professionals throughout the construction industry are increasingly required to use environmental assessment rating systems to evaluate building performance. Several frameworks are currently available to provide environmental assessments (Trusty 2000), but there is still a lack of highly efficient tools that can be used to manage the large amount of relevant data that needs to be collected in order to make an assessment; to consider effectively the nature and number of performance criteria and their influence on different construction project stages. The current practice of conducting environmental assessment manually and at the later stages of construction is not effective, since any improvement in achieving the desired performance has proved to be too expensive and time consuming (Kibert 2008). The construction industry needs to fundamentally innovate in the area of assessment culture and methodology in order to come up with something that could provide the opportunity to preview the overall performance of a project at every stage during a building's lifecycle.

In the remainder of this paper, Section 2 will outline the background of the regulations that are being considered in this work, with a description to existing work in the field of regulatory compliance, focusing specifically on other efforts within the AEC sector. The methodology of the new approach will then be described and, finally, two case studies that have been used for validation will be discussed in Section 4.

2. BACKGROUND

2.1 The Need for Automated Sustainability Compliance Checking

The emergence of Building Information Modelling as an integrated framework to manage building performance during its lifecycle is widely evolving and several researchers have conducted research with aims to integrate BIM with sustainability tools in order to achieve a high performance building (Everett, Boyle et al. 2012). Autodesk, (2005) has indicated that BIM makes an efficient contribution to achieving sustainable construction by "making the information required for sustainable design, analysis and certification routinely available simply as a by-product of the standard design process that can reduce the cost associated with traditional sustainability analysis and can improve energy performance." However, the full benefit of the integration of BIM with sustainability measuring systems still has to be considered in more detail (Dawood, Lord et al. 2009). To conduct

Citation: Kasim, T., Li, H., Rezgui, Y. & Beach, T. (2013). Automated sustainability compliance checking process: proof of concept. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

building performance assessment in the early design and preconstruction stage realistically, access to a comprehensive set of information and knowledge regarding a building's form, behaviour, management system, location, materials, context, and technical systems are required. Therefore, many researchers have investigated the integration between BIM and sustainability tools to overcome the previous difficulties (Biswas and Tsung-Hsien Wang 2008). The evolution of integrated BIM solutions has pushed for a new approach to an automation process assessing building compliance with regulations. The resulting approach reduces the violations to regulations that control the construction process. In the United Kingdom, there are several mandatory regulations that every building is required to comply with such as UK Building Regulations. These regulations basically contain the rules for construction work that every new and altered building need to comply with to improve the overall quality of the buildings, as well as making them safe and accessible with limited environmental damage. To facilitate checking compliance, Building regulations are supported by a statutory approved guidance document providing general guidance, practical examples and solutions to demonstrate how to achieve compliance. Compliance with these regulations is normally conducted manually by collecting and processing the relevant information (Regulation 2010). To assess the sustainability of new constructions of different building types, BREEAM (Building Research Establishment Environmental Assessment Method) was established in the UK in 1990. BREEAM is the first such comprehensive building performance assessment method (Lee and Burnett 2008). The main aim of introducing BREEAM was to mitigate the impact of buildings on the environment and to increase the recognition of buildings according to their environmental benefits (Global 2008). With the similarity to the approach of BREEAM assessment process, The Code for Sustainable Homes (CSH) has been introduced as the national standard for assessing, rating and certifying the sustainability performance of design and construction of new homes. These standards aim to encourage continuous improvement in sustainable construction design and to promote higher standards over the current standards set out by building regulation (McManus, Gaterell et al. 2010). BREEAM and CSH certification coupled with compliance with Building Regulation is a highly complex, rigorous and costly process; the huge amounts of data at every stage of the project make it difficult to conduct assessment and compliance checking continuously and accurately. In particular, when the assessment is considered at a later stage, it reduces the influence that these regulations can have on a project and may result in a desired rating being unobtainable or being obtainable only through additional investment.

2.2 Currently Available Solutions for Compliance Checking

The emergence of a rule checking environment has open the doors for researches to automate assessing the features and characteristics of a building design based on the information available in BIM model. The methodology applies a set of procedures to the information model and examines the compliance of a design, plan, action or performance with applicable codes and regulations and eventually results in a 'pass', 'fail' or 'unknown' warning messages for the assessed features (Nguyen and Asa 2006). There are several on-going studies that have been undertaken to automate compliance checking of building models against applicable laws and regulations. Pauwels, Van Deursen et al. 2011, have suggested four major software platforms which have been developed to support implementation aspects of rule checking systems. These are Solibri Model Checker, Jotne EDModelChecker, FORNAX and SMARTcodes. All these systems apply rules to Industry Foundation Classes (IFC) building model data. According to the approach followed for the indicated systems, the rule checking process is separated into four phases; these are a rule interpretation phase, a building model preparation phase, a rule execution phase, and a rule check reporting phase. These approaches are widely applicable and there are several application examples that have been stated by Eastman, Lee et al. 2009, such as CORENET-Singapore, Norwegian Statsbygg's design rule checking efforts, International Code Council (ICC) and General services administration design rule checking. Practically, these systems still have limitations in terms of interoperability (Tan, Hammad et al. 2010). Information for compliance checking requirements are not compatible with the information within the IFC file or in many cases some compliance checking requirements are not even available within the information model. The methodology applied in the previous approaches was to create IFC models with one of the BIM software such as Autodesk Revit architecture, Bentley, Google Sketch Up or ArchiCAD and then process the IFC files with SMC (State Machine Compiler), a java-based desktop platform to facilitate information access and processing (Salama and El-Gohary 2011). SMC has limitations such that any editing, modifications of existing rules, or addition of new rules have to be done by editing the original code by a person with knowledge of computer science. Most of the previous developments focus on the architectural and structural design domain, where efforts were exploited only to examine compliance with relatively simple form of rules such as dealing with geometrical or special attributes. For example, checking access dimensions, doors sizes, or wall thickness (Yang and Xu 2004). Automated compliance checking of performance and construction operations has only received little attention due to the complexity of the structure of performance related data. Existing tools lack the capability of performing logical compliance checking such as checking compliance with contractual requirement, quality control and construction's safety procedures where the information is not semantically represented in the BIM model.

3. SYSTEM OVERVIEW

The framework introduced in this paper is aimed at achieving an intelligent and integrated solution to make better decisions for sustainable construction, whilst achieving the desired building environmental performance with minimal errors and omissions. BREEAM, CSH and Building Regulations are considered in the current research. On this research, RASE methodology (Hjelseth and Nisbet 2010) has been utilized to convert standards and best practices into complied coded rules and to summarise data requirements for compliance checking as a possible enhancement of IFC for sustainability performance checking. The approach involved comparing the information within the IFC with the information needed for check and assessment. Once mapping occurs, new entities are added to the IFC. Figure 1 shows an overview of the current approach for automated compliance checking vs. the traditional manual approach.

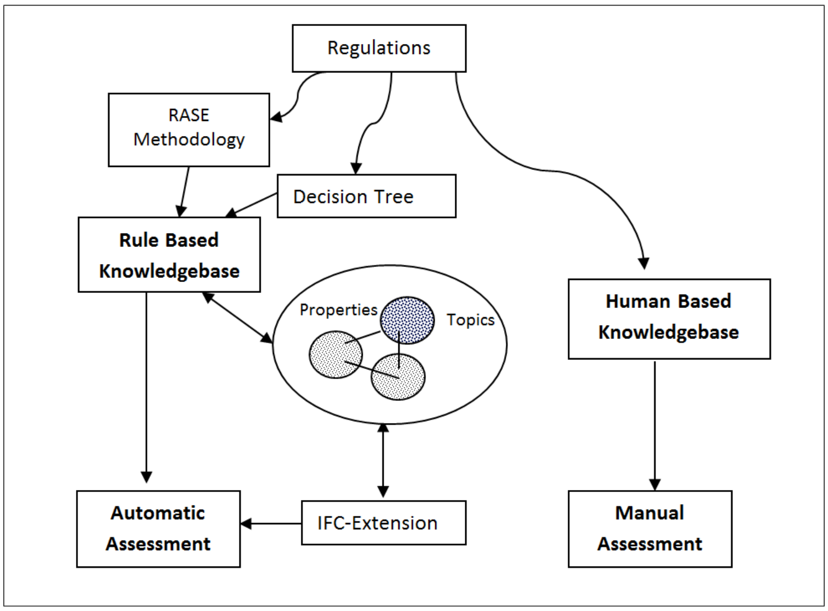


Fig. 1: System Overview

3.1 Automated Sustainability Compliance Checking Process VS Traditional Assessment Approach

The process of automated sustainability compliance checking is slightly different from the traditional manual approach. The proposed automated process relies on fastened records of project information presented in digital format rather than manual collection and re-organizing the accessible project data. Table 1 gives a summary of some of the pros and cons of the two approaches. Achieving an integrated automated compliance checking process is the field of interest of many researchers and stake holders however; the detailed coordinated workflow has not been precisely defined. The assessment procedure comprises different activities conducted by different parties. For example, energy efficiency performance measures, building element properties assessment and design aspects characteristics evaluation.

These actions require a coordinated work flow to address configuration of activities, roles of actors involved and packages of information exchange to achieve the optimum design that complies with sustainability standards. It is not within the scope of this paper to explain the full process, however, the context of the process is summarised in figure 2. The figure demonstrates exchange scenario between well-defined roles for a specific purpose within a particular stage of a project's life cycle. That can be abbreviated by what is known as "Use Case". Basically, a life cycle of the project is a series of use cases composed of detailed process parts. Every use case has a set of information that is exchanged between the involved actors (A1, A2, etc.). These sets of information represent exchange models (EM).

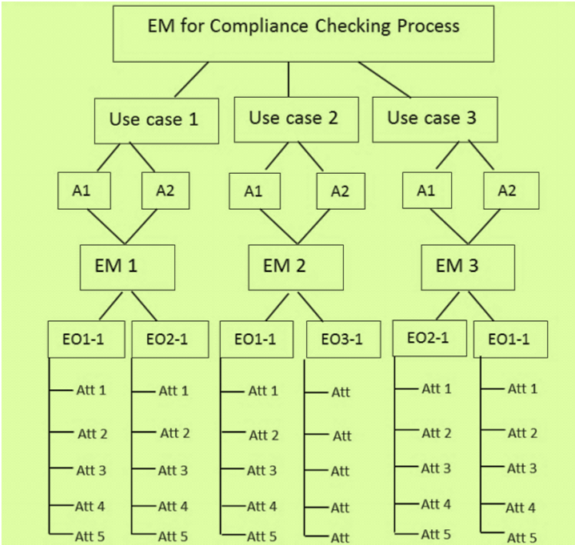


Fig. 2: Exchange requirement scenario

An exchange model comprises a list of exchange objects (EO) that encapsulates definitions of attributes for the exchange functional requirements. For example, a *building type* has several attributes that requires to be checked for compliance as shown in figure 4.

Generally, the process starts when the designer creates a BIM model for a proposed design in a BIM Authoring application, designers then save BIM as an IFC BIM. The IFC file should be comprehensive including sustainability related requirements. The compliance checking is completed by running the rule engine. Every object in the model should be checked for compliance with sustainability related standards (BREEAM, Building Regs and CSH) and generates a report and/or annotations in the model about issues of non-conformance with sustainability standards requirements. The automated process allows designers to be able to change the design such that it meets standards requirements and to satisfy the failed code requirements. The designer repeats the process until the design is fully conformant with these standards requirements.

Table 1: Comparison between traditional and automated compliance checking

Traditional sustainability assessment process	BIM based compliance checking
Required information is fragmented, needs to be gathered and re-organized to facilitate compliance checking	The BIM platform assembles Fasten record of information represented in digital format ready for the automated assessment process
Objects related attributes are not precisely attached but need to be collected separately	Objects are richly described with items such as a manufacturer’s product code, or cost, or date of last service
Errors are likely to occur due to a lack or constrains of information representation	The model holds all information in a single repository ensuring consistency, accuracy and accessibility of data to reduce errors and omissions of assessment
There is no linkage between the data created.	The BIM platform assembles all the required data for compliance checking into one location and cross-links that data among associated objects
The traditional assessment can assess all aspects of compliance checking	Some aspects cannot be assessed automatically when information cannot be represented in digital

	logical format
The assessor or compliance checker required to be an expert with wide knowledge of both assessment process and regulations requirements	The assessment can be conducted with a person with fair knowledge of the assessment process
Time consuming process	Faster and more effective processes information is more easily shared, it can be value-added and reused
Required hard human based efforts	Automatic compliance check relies on rule engine process
The assessment depends on available information and assessors experience	Depends on the information embedded within BIM model
Assessment Data is fragmented over the life cycle of the project	BIM model supports data over the complete project lifecycle from conception to demolition
The compliance check conducted after completion of the project	Can be conducted numerous times during the project stages for a better design
Human based documentation exposed to errors and omissions	Better production of quality documentation, output is flexible and exploits automation
Predictable assessment cost could not be reliable	Controlled predictable compliance checking cost
Any change of the design for better performance is time consuming and require further investment	Achieve optimized design that complies with standards and best practice.
Decreased implementation with the emergence of	Ultimately, a more effective and competitive
new technologies	industry

3.2 Extracting Compliance Requirements from Regulatory Documents

To define the main objects and their related attributes that are required to be checked for compliance, RASE methodology (Hjelseth and Nisbet 2010) has been utilized. The main objective of utilizing RASE is to convert text representation of compliance requirements from standards and best practices into complied coded rules. The principle behind the RASE concept is to add meta-data to human reading regulation documents. This is done using a mark-up based on the four operators; requirement (R), applicabilities (A), selection (S) and exceptions (E). See figure 3 (Hjelseth and Nisbet 2011). By deploying this method, the data requirements and the logical relationship between these requirements have been extracted by using the RASE tags. The assessment criteria have been imported into a software tool “Require 1” from AEC3 (Hjelseth and Nisbet 2010) and the data requirements have been fully extracted from the issues in the documents. This has enabled the required information for each issue to be summarized. Some text has been reformatted to facilitate this extraction. This is only required in a few issues where information is nested in a way that prevented the easy extraction of information. However, the vast majority of issues do not require any reformatting.

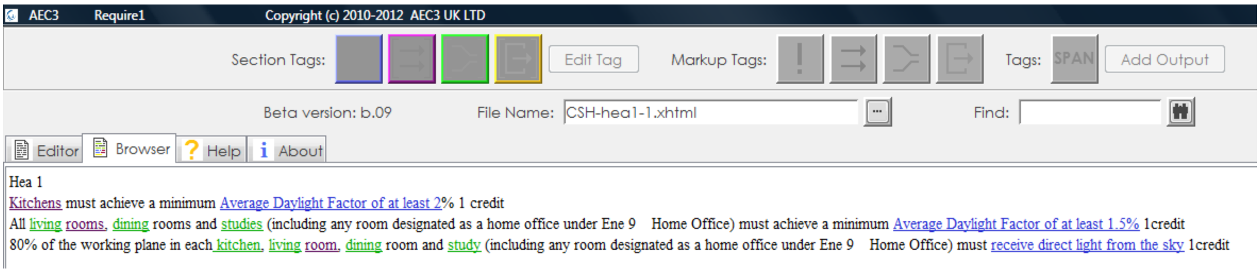


Fig. 3: The use of RASE tags

3.3 IFC for Compliance Checking Requirements

Generally, most of the compliance checking developments utilizes Industry Foundation Classes (IFC) to facilitate data exchange. IFC is the data developed by buildingSMART to facilitate data sharing between different applications for better interoperability (Fazio, He et al. 2007). It is registered by the ISO (International Organization for Standardization) and is currently known as the mainstream standard for BIM (Vanlande, Nicolle et al. 2008). IFC Standard is a complex data standard. It covers nine domains of information such as Building control, structural elements, HVAC, etc. (Eastman 2006). The data structure is based on 3D geometric models and object oriented specification. In spite of its complexity, IFC has efficiently supported software applications for more than 20 venders (Zhiliang, Zhenhua et al. 2011). While the richness of information offered by IFC is evident, there are still tremendous challenges in getting comprehensive representation of performance-specific information ready for extraction for direct compliance checking. By deploying RASE methodology, a list of data requirement for compliance checking has been summarized to append possible enhancement for the IFC. The inference of RASE implementation outlined the terms that occur within the regulation documents. This implementation expedite mapping between the regulation terminology and the terminology that the IFCs perform. Figure 4 shows an example of this. In this figure, the solid arrows represent mappings within the context and the dotted arrows show mappings that the dictionary makes between the terminology used in the regulations and the IFCs. In Figure 4 the object *Building* and its two properties *UsedForFlammableStorage* and *is ShellOnly* that are extracted from the meta-data are added to the BREEAM regulations. These are mapped by our dictionary to their counterparts in the IFC model. "Building" is mapped to *IFCBuilding*; *UsedForFlammableStorage* is mapping to a *FlammableStorage* data item within the *PSET_SpaceFireSafetyRequirements* property-set of an *IFCBuilding*; and *is ShelOnlyl* does not map directly to data within IFCs so it is mapped to a newly added data item within our IFC extensions.

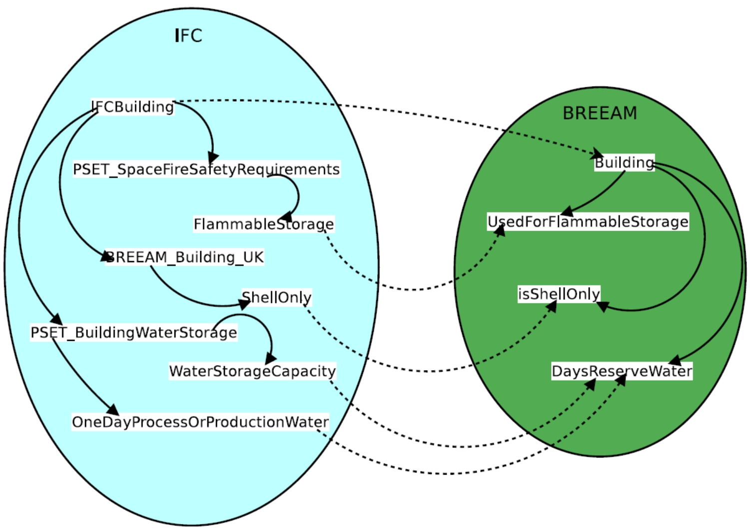


Fig. 4: Mapping Between IFC and BREEAM

3.4 Rule Execution Process

Since there is no satisfactory traditional programming approach to execute the requirement for sustainability compliance checking automation, the decision has been made to use a rule engine, The choice of the rule engine is based on several factors; for example, it must meet the requirements for the executable rules and also the rule engine must be open source and commonly used for similar approaches. Therefore, DROOLS rule engine has been utilised. DROOLS possess interesting features that allows the possible addition of incremental compliance checking features. For successful implementation of the process, it is critical that a checking model is designed with the proper data interface to the rule engine. The mapping process verifies that every set of data occurs within the BIM model/IFC file has a separate, equivalent set of rules within the rule engine system. This is shown in figure 5.

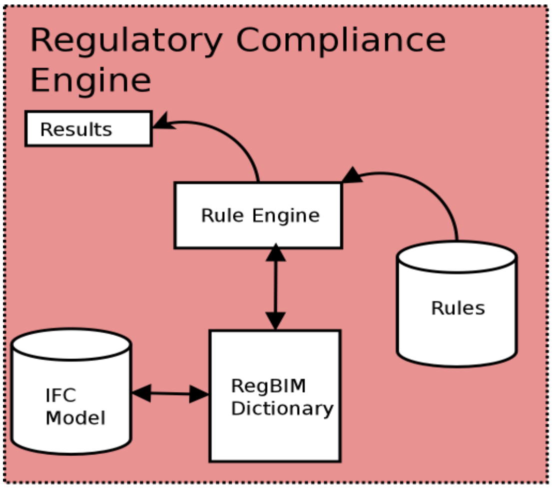


Fig. 5: Rule engine

In order for the DROOLS rule engine to process the meta-data that has been added as RASE to the regulations documents, the RASE tags have been converted into a format understandable by the rule engine, namely DRL (DROOLS Rule Language). This is done by using a rule compiler to apply the logical expansion shown in Figure 6 to the RASE tags that have been applied to the rule (Hjelseth and Nisbet 2010). The DRL is then converted by DROOLS into executable code. New sets of rules can be added to the system with no effect on the existing rules. This, in short, means that in order for a rule to be passed as true at least one of the following must occur:

- The rule is NOT applicable – at least one of the applicabilities (A1, A2 …) is not met.
- The rule meets one of its exception criteria (E1 or E2 are true).
- The rule fails to meet all of its selection criteria (S1 and S2 are both false)
- All requirements within the rule are met (R1, R2 and R3 are true)

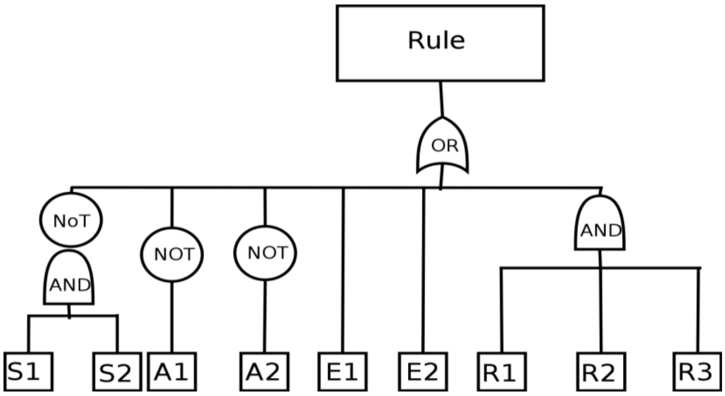


Fig. 6: RASE Logical Expansion

Figure 7 shows a sample clause and the DRL produced by running this clause through the compiler. Examining the clause, we can see that the clause is verifying if the principal contractor has a suitable score from the considerate construction scheme. This clause has one application: that the rule only applies to contractors that are the "principal" contractor and two requirements: that the CCS (Considerate Constructors Scheme) score is greater than 24 and that it is less than 31.5. The DRL shown illustrates that the rule will loop through all contractors that meet the application defined in the clause and check that the CCS score is within the defined limits.

Where the principal contractor achieves compliance with the criteria of a compliant scheme, CCS score between 24 and 31.5

```
rule BREEAM_MAN2_1-1
when
        forall ($contractor: Contractor(type=='principal')
               Contractor( this==$contractor, ccs_score >= 24 , ccs_score <=31.5)
        )

then
        results.pass("BREEAM_MAN2_1-1");
end
```

Fig. **7**: An example RASE clause and its translation into DRL

Internally within the rule engine the DRL rules that make the decisions use data stored in a standard object model. In figure 8 we have one object, *Contractor,* which has two properties, *type,* and *ccs_score.* It is important to notice these names are taken directly from the RASE meta-data to form its rules.

4. VALIDATION

Initial trials of the system have taken place and the results have proved very promising. Two case study issues have been tested; ECO5 from Code for Sustainable Homes and MAN2 from BREEAM. ECO5 tests development sites' protection of ecological features and MAN2 tests whether construction sites are managed in an environmentally and socially responsible and accountable manner. To validate both of these issues, a test IFC dataset has been used and the compile rules have been executed by the rule engine and checked by an expert to ensure the results are correct.

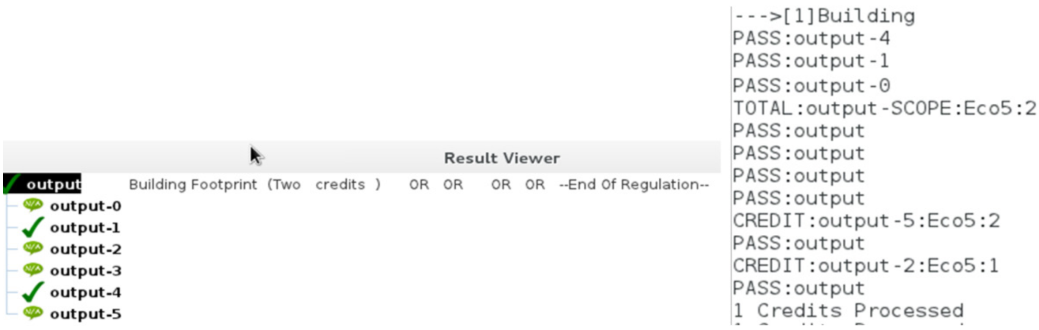


Fig. 8: Visualised Output from Eco5

Figure 8 shows the visualised and raw results from one of the Eco5 tests. We can see from this example that the rule is structured as a single OR with 6 possible options. Two of these options have been passed, meaning that the result is true. The raw result output also shows that credits have also been awarded for each of the options that have been passed. It should be noted that the credits are awarded twice for Eco5, this is because two of the options have passed when only one was required, the post processing, however, understands this possibility and only considers the highest value awarded.

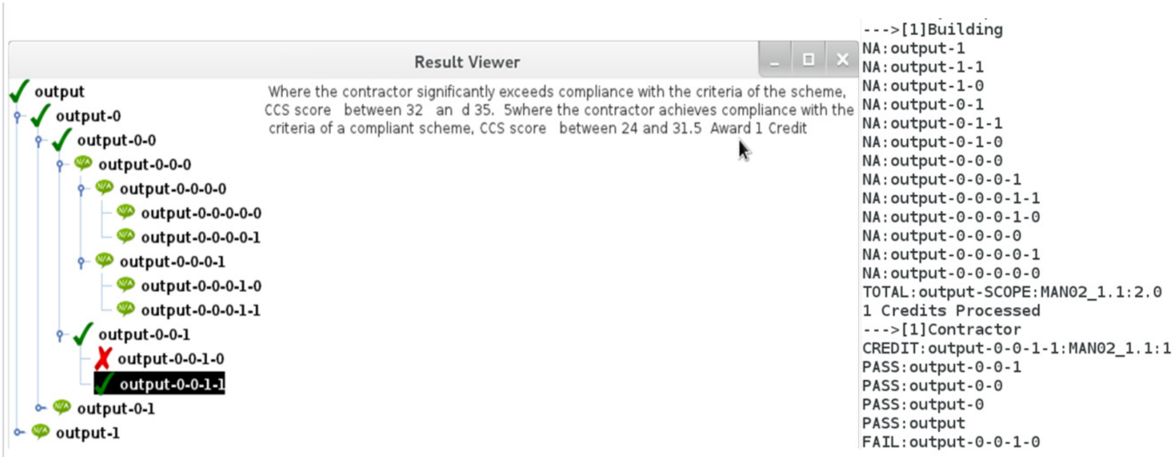


Fig. 9: Visualised Output from Man2

Figure 9 shows an equivalent set of results for the more complex Man2 issue. This issue has a more deeply nested structure of requirements, a large number of which are not applicable in this example. In this particular example, the only particular branch that is applicable is *output-0-0-1*. This is an OR choice between two options in which one fails and the other passes, meaning the regulation itself is true. Once again the raw output shows that credits have been awarded for the pass result.

5. CONCLUSION

This paper introduces a new approach for automated sustainability compliance checking. In contrast, current environmental assessment practice is lacking automatic synchronisation of the domain and rich semantic modelling. It is limited to the simpler querying of the manually maintained model. The rule based compliance checking approach relies on converting standards and best practices into complied coded rules by using a modification of the RASE methodology. This methodology allows the rules to be generated rapidly and extracts the need for manipulation of the compiled rules themselves. This is a critical issue that allows the rules to be in a form understandable by construction domain specialists without needing to understand the industry data file formats or even how the underlying rule engine will work.

On this research, a general overview on sustainability related information available in IFC standard is summarised and a list of data requirements is defined in order to be added to the IFC specification and this will be contributed back to BuildingSmart (the standardisation body for the IFCs) in the form of an extension proposal covering regulatory compliance. While our initial work has focused on the development of a regulatory compliance system for the AEC sector, it is anticipated that our approach is generalizable to many other related industries. However, when adapting the approach modifications may need to be made to the meta-data used to support specific ways in which a particular industry operates. This will be similar to the modifications made to adapt RASE in Section 5.1 to support the balanced-scorecard regulations common in the AEC sector.

Finally, for the validation process, this paper gives preliminary results for two examples of compliance checking on issues extracted from BREEAM and CSH. In future studies, the development will be implemented on a real case study to conduct a comparison between the manual approach and rule based approach for compliance checking. Also, it is promising that the system will be expanded to be integrated closely with an industry standard design package to enable dynamic requirement checking as a designer designs their building.

6. REFERENCES

Biswas, T. and R. K. Tsung-Hsien Wang (2008). "Integrating sustainable building rating systems with building information models."

Dawood, S., R. Lord, et al. (2009). Development of a visual whole life-cycle energy assessment framework for built environment. *Simulation Conference (WSC), Proceedings of the 2009 Winter, IEEE.*

Eastman, C. (2006). "IFC overview." Chuck Eastman.

Eastman, C., J.-m. Lee, et al. (2009). "Automatic rule-based checking of building designs." *Automation in Construction* 18(8): 1011-1033.

Everett, R., G. Boyle, et al. (2012). Energy systems and sustainability: power for a sustainable future, Oxford Univerity Press.

Fazio, P., H. He, et al. (2007). "IFC-based framework for evaluating total performance of building envelopes." Journal of architectural engineering 13(1): 44-53.

Global, B. (2008). "BRE Environment & Sustainability Standard (BES 5055: ISSUE 3.0)." BREEAM Offices

Hjelseth, E. and N. Nisbet (2010). Exploring semantic based model checking. *Proceedings of the 2010 27th CIB W78 International Conference.*

Hjelseth, E. and N. Nisbet (2011). Capturing normative constraints by use of the semantic mark-up (RASE) methodology. *CIB W78 2011 28th International Conference-Applications of IT in the AEC Industry.*

Kibert, C. J. (2008). Sustainable construction: green building design and delivery, wiley.

Lee, W. and J. Burnett (2008). "Benchmarking energy use assessment of HK-BEAM, BREEAM and LEED." Building and Environment 43(11): 1882-1891.

McManus, A., M. Gaterell, et al. (2010). "The potential of the Code for Sustainable Homes to deliver genuine 'sustainable energy'in the UK social housing sector." Energy Policy 38(4): 2013-2019.

Nguyen, T.-H. and E. Asa (2006). Integrating building code compliance checking into a 3D CAD system. Proc. of Joint International Conference on Computing and Decision Making in Civil and Building Engineering.

Pauwels, P., D. Van Deursen, et al. (2011). "A semantic rule checking environment for building performance checking." *Automation in Construction* 20(5): 506-518.

Regulation, U. B. (2010). Building and Buildings, England and Wales, http://www.legislation.gov.uk/uksi/2010/2214/contents/made. No. 2214.

Salama, D. and N. El-Gohary (2011). Semantic modeling for automated compliance checking. Proc., 2011 ASCE Intl. Workshop on Comput. in Civ. Eng.

Tan, X., A. Hammad, et al. (2010). "Automated code compliance checking for building envelope design." Journal of Computing in Civil Engineering 24(2): 203-211.

Tan, Y., L. Shen, et al. (2011). "Sustainable construction practice and contractors' competitiveness: A preliminary study." Habitat International 35(2): 225-230.

Trusty, W. B. (2000). "Introducing an assessment tool classification system." *Advanced Building Newsletter* 25: 18.

Vanlande, R., C. Nicolle, et al. (2008). "IFC and building lifecycle management." *Automation in Construction* 18(1): 70-78.

Website, D. P. Retrieved February, 2013, from http://www.jboss.org/drools/.

Yang, Q. and X. Xu (2004). "Design knowledge modeling and software implementation for building code compliance checking." Building and Environment 39(6): 689-698.

Zhiliang, M., W. Zhenhua, et al. (2011). "Application and extension of the IFC standard in construction cost estimating for tendering in China." *Automation in Construction* 20(2): 196-204.

AN EVALUATION OF IMMERSIVE VIRTUAL REALITY SYSTEMS FOR DESIGN REVIEWS

Fadi Castronovo, Dragana Nikolic, Yifan Liu & John Messner

Department of Architectural Engineering, The Pennsylvania State University, University Park, PA16802

ABSTRACT: *With the growth of building information modeling (BIM) approaches to facility design, architectural, engineering, and construction (AEC) industry has been shifting to the use of three-dimensional (3D) virtual facility mockups during design. Studies have shown that 3D models when displayed in an immersive projection display environment allow users to interact with the virtual environment at full scale, and review the designed space in a more intuitive manner. Virtual environments and VR systems however, can vary greatly in levels of immersion and user experience they offer. Thus, for a novice user choosing an appropriate and effective system for specific tasks can be daunting. To understand the benefits of specific VR systems for facility design, this research presents results from conducting design reviews in two immersive display systems. The first system was a fully immersive 5-wall CAVE™ environment, while the second was a semi-immersive 3 screen display system. For each design review, the user experience of a reviewing team was documented and analyzed through targeted questionnaires. The large screens, field of view, level of immersion and the overall value of both systems for design reviews were rated consistently high. Furthermore, based on the comments provided by the project team, the fully-immersive system was found to be more appropriate for smaller groups that desire a higher level of immersion. Additionally, the semi-immersive system with a larger footprint was found to be more suitable for larger groups for various use cases. These results aim to guide future users to make an informed decision when selecting an appropriate immersive display system.*

KEYWORDS: *virtual construction, virtual reality, design review, immersive projection*

1. THE DESIGN REVIEW PROCESS

In architecture, engineering, and construction (AEC) the review of a proposed design is an essential step. Facility design progresses from early conceptual and schematic design to later design development and construction. Each design stage serves to share and communicate project information to provide feedback and check for inaccuracies, or other types of conflicts (East, 1998). How the project information is represented can have a significant effect on understanding the design and providing meaningful feedback.

The design process starts with problem recognition and problem definition in the early conceptualizing stages (Yessios, 1987). The final physical form evolves from numerous iterations of the proposed design solution. During the entire design process and throughout stages, designers use representations to externalize their ideas about the function and the aesthetics of the designed object. The design process is represented at different stages with varying levels of information. When defining the problem in the early stages of the design, designers use more symbolic and abstract representations such as diagrams or schemes. During later stages, as design evolves, representations of the designed object become more detailed and illustrative of its intended physical appearance. Design activities inherent in this design process can also be categorized as *generative* – generating partial solutions and *evaluative* – evaluating proposed solutions (Coyne and Subrahmanian, 1993). In architecture and engineering design, emphasis is placed on the evaluation of the proposed solution. The design solution is evaluated to detect any possible failure with respect to program, function of spaces or overall performance. This process is known as a design review. It is necessary to understand the design in order to evaluate and critique it. Throughout the process, representations are used as a tool for understanding both the design problem and its solution. External representations such as drawings, or scale models as well as internal representations in the form of mental images play an important role in the design process. Representations enable an understanding of the proposed design solution and allow for a meaningful critique (Kalisperis et al., 2002). A valuable external representation is therefore one that requires less translation of the information and allows ideas to be communicated and thus evaluated more easily. By overcoming the cognitive limitations, an appropriate representation becomes a powerful aid in enhancing the reasoning and creative process (Rice, 2003).

Citation: Castronovo, F., Nikolic, D., Liu, Y. & Messner, J. I. (2013). An evaluation of immersive virtual reality systems for design reviews. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Currently, the most prominent method of conducting design reviews is through the use of 2 dimensional (2D) Computer Aided Design (CAD) digital or paper drawings. Previous research suggests that traditional representational mediums such as drawings or scale models are limiting because of the additional effort needed in visualizing space and movement through it (Khemlani et al., 1997). This is mainly due to the fact that the user has to extrapolate the scale of the model to one's own scale. This scale difference limits the ability to experience the space as it is intended and the experience itself can differ immensely from the real scale models (Henry and Furness, 1993). Shiratuddin (2009), and Fu and East (1999) describe the design review process in three steps. In the first step, the reviewer analyzes the drawings and specifications of the design. In the following step, based on rules of thumb and practice standards, the reviewer annotates the drawings' mistakes and omissions. Lastly, the reviewer sends the marked drawings back to the designer, who then integrates the proposed changes. The review process of drawings is conducted through the use of light tables, checklists, and physical mockups. According to Staub-French & Fischer (2001), the overlay process of light tables is highly inefficient and time-consuming. Meanwhile, the electronic or physical checklists process relies on the crosschecking of drawings. This process has also proven to be highly inefficient (Nigro, 1992). Additionally, physical mockups can be developed for the review of the design. However, physical mockups can have a high cost and long construction time (Shiratuddin, 2009). Three-dimensional (3D) computer models have largely replaced the physical scale models allowing easier modifications to the design. The use of building information modeling (BIM) software has showed its value in the visualization of design information (Leicht et al., 2009). The growing adoption of BIM tools is mainly related to the user's ability to directly interact with the 3D model (Tse et al., 2005). However, many of the BIM software focus on supporting the facility design process, and not necessarily on supporting the design review process (Shiratuddin and Thabet, 2011).

2. IMMERSIVE VIRTUAL REALITY FOR DESIGN REVIEW

One method to improve the information representation is through the development of virtual prototypes that can be experienced in virtual reality (VR) environments. Virtual reality is commonly referred to as a computer-generated environment that offers a viewer a convincing illusion and a sensation of being inside an artificial world that exists only in the computer. VR is thus often referred to as *immersion technology*, though the extent of immersion may vary based on the system characteristics and context of virtual model. Immersion refers to a level of sensory fidelity which depends on measurable system attributes such as field of view (FOV); display size; stereoscopy; display resolution; head-tracking; or input devices among other (Slater and Wilbur, 1997; Bowman and McMahan, 2007). Although immersion is a multidimensional construct, based on the presence of specific system components, broad categorization of VR system types include non-immersive systems such as desktop computer systems; *semi-immersive* with large, multiple screens or monitors that provide a medium to high level of immersion; and *fully immersive* systems such as head-mounted displays (HMD) or CAVE™ systems with three or four walls, a projected floor, and possibly even a projected ceiling which significantly or fully cover the users' field of view.

What sets virtual reality apart from other traditional media is the capability to present spatial information in a more engaging manner, allowing for interaction with designed spaces at a human scale. While stereoscopy is one of the defining features of immersive VR systems, large screen size and wide field of view are critical in allowing for more spatial information and alleviating the scale problems characteristic of traditional media. Content-wise, texture, lights, shadows and objects contribute to the overall VR experience and also act as depth cues affecting the perception of spaces. These VR attributes can further augment the richness of information and possibly enhance the visualization process. For its potential to support experiential learning, movement through space and time, and interaction with the design, VR is being increasingly used in architecture, engineering and construction. In the evaluative stages of the design review process, these VR attributes can contribute to understanding specific design features such as scale, dimensions, or layout; complementing existing forms of representation. Virtual reality enables a more qualitative representation of spaces from the users' perspective by using 3D spatial information full scale, and creating the illusion of depth and immersion.

Virtual prototypes have become increasingly used in many areas in the last decades (Kumar et al., 2011). In architecture and construction, virtual prototypes have shown value for their ability to present both small-scale and large-scale three-dimensional spatial information. Compared to standard approaches to building physical mockups and its low cost compared to traditional design reviews, especially physical mockups. Benefits in conducting design reviews using virtual prototypes have been demonstrated in a case study for a courtroom design (Maldovan and Messner, 2006) and in the design review process of operating and patient rooms (Dunston et al., 2007). Kumar (2011) has shown the benefits of interactive virtual prototypes in design reviews of healthcare facilities. Successful applications of virtual reality have been demonstrated in visualizing construction schedules for nuclear power plants (Whisker et al., 2003) as well as in a growing industrial use in the construction contracting, engineering consulting and development (Whyte, 2003). However, most users lack experience in using immersive virtual environments for design reviews due to availability of such facilities. Depending on the user group and their experience, selecting an appropriate immersive display system can be challenging. Shiratuddin et al. (2004) compared all three types of systems for their suitability in decision making tasks in construction. Specifically, using both summative and formative evaluation techniques, the systems were compared by their visual quality, physical comfort, level of realism, ease of navigation, and way-finding. Four-screen (3 walls and a floor) cube-like display was consistently rated higher compared to non-immersive (monitor) and fully immersive HMD, for its higher level of realism, field of view (270^{o}), sense of scale, and overall suitability for design/planning and decision-making tasks. Features such as stereoscopy, large screen, and wide field of view with varying level of detail have demonstrated to effect the level of presence and spatial understanding of the designed space in architecture (Nikolic, 2007; Zikic, 2007).

While immersive systems with large screens and wide fields of view contribute to a higher sense of presence and realism, they are typically associated with higher costs and a learning curve for the end user in both developing the content and using the system. The question is then whether the system provides specific benefits to the task to justify the expense and the complexity of the system. Understanding the advantages and tradeoffs between different system configurations can help potential users make an informed decision when choosing an appropriate system.

3. A COMPARISON OF IMMERSIVE SYSTEMS FOR DESIGN REVIEWS

The research team conducted a study to evaluate the similarities and differences between performing a design review in a semi-immersive display environment and a fully immersive display environment. To contribute to a better understanding of suitability of specific VR features for conducting design reviews, the research team compared a design review process in two types of immersive systems with large screens and wide field of view – an open footprint semi-immersive lab partially surrounding the user (Figure 1) and a 5-screen, fully-immersive lab with four projected walls and a floor fully surrounding the user (Figure 2).

Fig. 1: Semi-immersive display system housed in the ICon lab at Penn State

Fig. 2: Fully-immersive display system (image courtesy of ARL)

3.1 The Display Systems' Characteristics

To compare the systems the research team used in-house facilities located at the Pennsylvania State University. The *semi-immersive* display system, housed in the Immersive Construction Laboratory (ICon Lab) in the Architectural Engineering Department, has an open footprint space with three stereo-enabled 8 foot by 6 foot rear-projected screens joined at 135 degree angles. Each of the displays has a resolution of 1600 x1200, for a total system resolution of 4800 x1200. The display also features a user tracking system with an Xbox tracked controller which was used for the design review activity. Head tracking, however, was disabled during the design review to maintain a consistent viewpoint for all the participants.

The *fully immersive* display system located in the Synthetic Environment Applications Laboratory (SEA Lab) housed in the Applied Research Laboratory (ARL) has a 5-sided CAVE^{TM}-type immersive projection display system providing a 360-degree view. Each of the screens is 10 feet by 9 feet with a floor footprint of 10 feet by 10 feet. The display system also features user tracking with head tracked glasses and tracked navigation with an Xbox controller. Both display systems allow users to collaboratively interact with large 3D models and simulations in real-time.

3.2 The Design Review Procedure

The two labs hosted the team of nine participants including two future facility occupants, four owner's representatives, two architects, and a construction manager to review the design of a new building to house an academic department on a large university campus. The new four-story 72,000-square-foot building will contain offices, classrooms, meeting rooms, and a full height atrium. Particular attention in the design review was given to the 4 story atrium because of its interior architectural wooden cladding panel system. To prepare the virtual mockup for the design review, the 3D model developed by the project architects was imported by the research team into the Presagis Vega Prime™ 3D visualization software through Autodesk 3D Studio Max (Figures 3 and 4). Once the model was imported, surrounding buildings and topography were added. Also, as requested by the review team, an interactive feature was added to the virtual mockup to allow changing the material appearance of the wooden panels located in the atrium (Figure 4).

The first design review was conducted in the fully-immersive (SEA) lab, where the project team reviewed the design by walking through the model, reviewing specific areas, and changing the textures in the atrium. The second design review followed in the semi-immersive (ICon) lab using the same walkthrough procedure of the same model. The walkthrough sequence, navigation, and the review process were kept consistent between the two labs. Following the design reviews, a total of three surveys were administered. Feedback was collected using both open-ended questions and 5-point Likert scale items ranging from strongly disagree to strongly agree. Figure 5 illustrates the sequence of the design review conducted by the project team.

Fig. 3: Virtual mockup – exterior view

Fig. 4: Atrium view with the wooden cladding

Fig. 5: Design Review Procedure

The first and the second survey administered at the conclusion of the design reviews in the fully- and the semi-immersive environment respectively, aimed to evaluate the effectiveness of the systems' attributes such as large screens, field of view, stereoscopy and level of immersion for the design review. The users were asked to rate their sense of presence in the virtual model; the sense of movement through the space; and the appropriateness of the scale of the model and its objects. Additionally, participants were asked to rate the usefulness of the ability to change the model textures. For each of the surveys, a total of 9 data points were collected. The last, third survey, administered after the second design review asked users to compare and rate the appropriateness of the two systems for different tasks such as design/construction/coordination reviews and different user groups. The first section aimed to directly compare the effectiveness and usability of the systems' immersive features. Participants were asked to rate how useful the 360^{o} field of view of the fully immersive system was compared to the 135^{o} field of view of the semi immersive system. The second section asked participants to rate the appropriateness of the two systems for future specific use cases such as small and large groups of users, operational staff, project teams, and contractors. Specifically, participants were asked to evaluate the two system types' suitability for the following types of reviews – design reviews with a small or large group of users, project team, and operational staff; construction reviews with a small or large group of contractors and project team; and coordination, clash, and trade meetings with a small or large group of contractors and project team.

4. RESULTS AND DISCUSSION

The results indicate very little variance in the overall highly rated effectiveness of the two systems, although the small sample size does not warrant significant statistical conclusions. The average ratings of the two systems indicate that the fully-immersive system slightly outperformed the semi-immersive system in providing a higher sense of presence and compelling sense of movement though the model (Figure 6). On the other hand, the semi-immersive environment was rated slightly higher for its higher screen resolution and the effectiveness of changing of the textures (Figures 6 and 7). While the large screen size was equally, highly rated in both systems, the team found the objects to be somewhat more properly sized in the semi-immersive environment, possibly due to the limitation of tracking only one person's viewpoint in the CAVE^{TM}. Overall, the data from the first two surveys indicate very little difference in the effectiveness of the two display systems for reviewing the design.

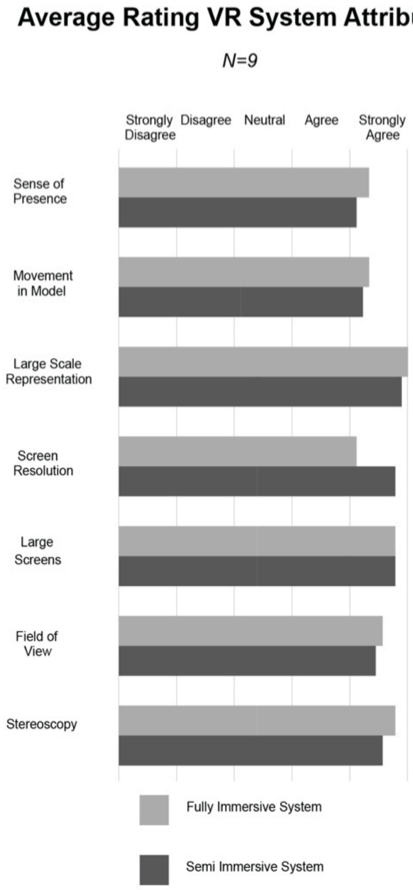


Fig. 6: Rated helpfulness of the two systems' VR attributes

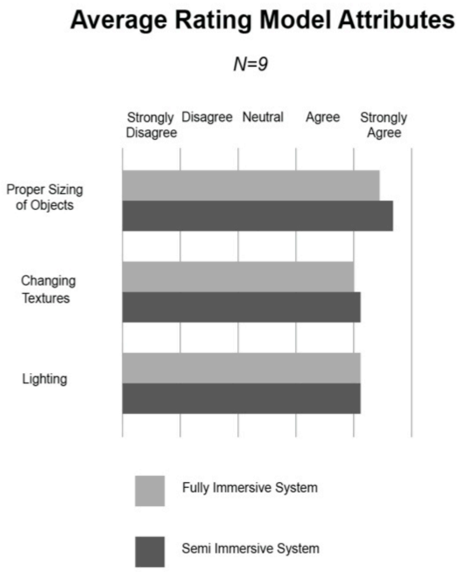


Fig. 7: Rated helpfulness of model attributes

The results from the third survey however, indicate potential differences in the suitability of the two labs for conducting different tasks with different user groups. The project team rated a fully-immersive environment to be slightly more appropriate in conducting future design reviews for smaller groups of users, project teams, and operational staff (Figure 8). However, the participants also confirmed that a semi-immersive system would be considerably more appropriate for larger groups of users, projects teams, and operational staff due to its open footprint. As shown in Figure 9, for conducting future construction reviews, the project team found the semi-immersive system marginally more appropriate for larger groups of contractors and project teams. Similar to future design reviews, the team found the semi-immersive system to be better suited for larger groups conducting clash and coordination reviews (Figure 10)

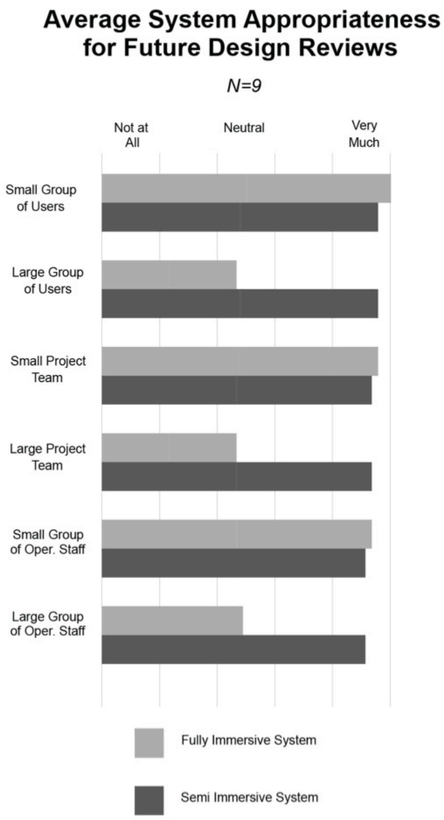


Fig. 8: Design Review Evaluation

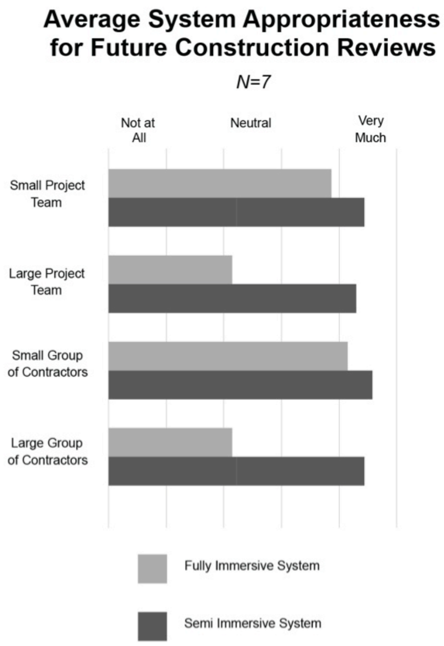


Fig. 9: Construction Review Evaluation

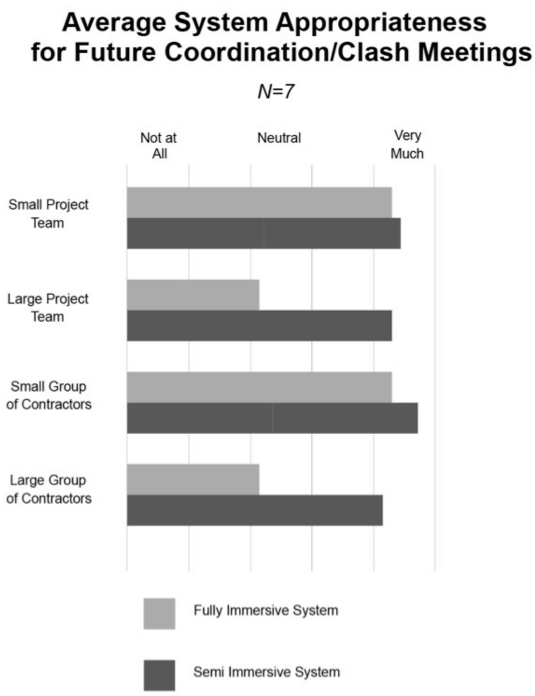


Fig. 10: Coordination/Clash/Trade Meeting Evaluation

The participants' comments provided additional insight into the results. Seven team members favored the surround, 360^o field of view of the fully-immersive environment (4.89, *N*=9) compared to semi-immersive (3.89, *N*=9) because it allowed an easier movement inside the building and provided a higher sense of "reality". One participant commented that the fully immersive environment felt like being "inside" the model, while the semi-immersive environment felt like only viewing the model. On the other hand, while five participants felt the higher level of immersion was more valuable for the design review, three participants did not see an increased value. One of the participants who rated 360^o field of view higher, commented that the wider field of view did not have a greater advantage overall. Lastly, one of the participants suffered from vertigo and expressed difficulty in conducting the review in the 360^o field of view environment.

5. LIMITATIONS

Although the results indicate a relatively small difference in the overall effectiveness of the semi- and fully-immersive display systems for the design review task, there are a number of limitations of this case study. Design review is standard and a critical step in the design process. However, very rarely do design review teams have an option to use two different types of display systems. For the duration of this case study, the research team managed to find one project team who agreed to perform design review in both facilities. Therefore the data was collected from a small number of participants limiting the ability to draw broad conclusions about the effectiveness of the systems. In addition, the two design reviews were conducted successively with the review in the semi-immersive lab following immediately after the review in the fully immersive lab. While this ensured the participants were in the consistent "mood" and equivalent experience, the order of facilities may have impacted the participant perceptions of the two systems. For example, due to time constraints in both reviews, the participants may have identified different design issues in either of the systems, which may have affected their perception of the systems' effectiveness. Another limitation was the difference in the navigation methods used in the two systems. User-tracking was used in the fully-immersive but not in the semi-immersive system, where only the Xbox control was used for navigation. This difference in navigation method may have affected the users' sense of immersion.

6. CONCLUSIONS

The review of a proposed design is a critical step in the preconstruction phase. Identifying design errors through a high quality design review using VR in the early stages of design can yield considerable benefits. However, broad spectrum of VR systems ranging in configuration, cost, and features may present users with a challenge of choosing an appropriate system based on the task.

To gain a better understanding of the suitability of different immersive systems for specific uses in the AEC industry, the research team compared a semi-immersive and a fully-immersive system. While the sample size was limited (9 participants), the results indicate few difference in the effectiveness of the two systems. The large screens, field of view, level of immersion and the overall value of both systems for design reviews were rated consistently high. When group size and task are considered key differences were found. For example, based on the comments provided by the project team, the fully-immersive system was found to be more appropriate for smaller groups that desire a higher level of immersion. Furthermore, the semi-immersive system, which has a lower level of immersion, but a larger footprint, was found to be of higher suitability for larger groups for various use cases. These results should allow for future project teams to critically choose an immersive display system that suits their needs, whether it is a higher sense of immersion or larger footprint. The future steps will include conducting experiments with a larger group of different user groups in conducting design reviews of various types of facilities.

7. REFERENCES

Bowman, D.A., McMahan, R.P., 2007. Virtual Reality: How Much Immersion is Enough? Computer 40, pg. 36–42.

Coyne, R.F., Subrahmanian, E., 1993. Computer supported creative design: A pragmatic approach, in: Gero, J.S., Maher, M.L. (Eds.), Modeling Creativity and Knowledge-Based Creative Design. Hillsdale, NJ, Lawrence Erlbaum Associates, pg. 295–327.

Dunston, P.S., Arns, L.L., McGlothin, J.D., 2007. An Immersive Virtual Reality Mock-Up for Design Review of Hospital Patient Rooms, in: CONVR 2007. Presented at the Seventh International Conference on Construction Applications of Virtual Reality, Penn State University, University Park, PA, pg. 9.

East, W.E., 1998. Web-Enabled Design Review and Lessons Learned (No. CERL Report No. A 396443). Champaign, IL: U.S. Army Corps of Engineers Construction Engineering Research Laboratories.

Henry, D., Furness, T., 1993. Spatial Perception in Virtual Environments: Evaluating an Architectural Application, in: VRAIS '93 Proceedings of the 1993 IEEE Virtual Reality Annual International Symposium. IEEE, Washington, D.C., pg. 33–40.

Kalisperis, L.N., Otto, G., Muramoto, K., Gundrum, J.S., Masters, R., Orland, B., 2002. Virtual reality/space visualization in design education: the VR-desktop initiative, in: Proceedings of eCAADe2002, Design E-ducation: Connecting the Real and the Virtual. Warsaw, Poland, pg. 64–71.

Khemlani, L., Timerman, A., Benne, B., Kalay, Y.E., 1997. Semantically Rich Building Representation, in: Proceedings of ACADIA '97, Design and Representation. Cincinatti, Ohio, pg. 207-227.

Kumar, S., Hedrick, M., Wiacek, C., Messner, J.I., 2011. Developing an experienced-based design review application for healthcare facilities using a 3d game engine. ITcon Vol. 16, Special Issue Use of Gaming Technology in Architecture, Engineering and Construction, pg. 85-104.

Leicht, R., Messner, J., Anumba, C., 2009. A framework for using interactive workspaces for effective collaboration. ITcon, Special Issue Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning 14, pg. 180–203.

Maldovan, K., Messner, J., 2006. Determining the effects of immersive environments on decision making in the AEC Industry, in: Joint International Conference on Computing and Decision Making in Civil and Building Engineering. Montreal, Canada.

Nikolic, D., 2007. Evaluating relative impact of virtual reality components detail and realism on spatial comprehension and presence (M.S. Thesis). The Pennsylvania State University, University Park, PA.

Rice, A., 2003. Exploring the Impact of Emerging Landscape Visualization Tools on Spatial Perception and Design Education, in: Buhmann, E., Ervin, S. (Eds.), Trends in Landscape Modeling. Heidelberg: Wichmann, pg. 173–182.

Shiratuddin, M.F., 2009. A Framework for Design Review in a Virtual Environment: Using Context Aware Information Processing. VDM Verlag.

Shiratuddin, M.F., Thabet, W., 2011. Utilizing a 3D game engine to develop a virtual design review system. ITcon Vol. 16, Special Issue: Use of Gaming Technology in Architecture, Engineering and Construction, pg. 39-68.

Shiratuddin, M.F., Thabet, W., Bowman, D., 2004. Evaluating the effectiveness of virtual environment displays for reviewing construction 3D models, in: CONVR 2004. Lisbon, Portugal, pg. 87–98.

Slater, M., Wilbur, S., 1997. A Framework for Immersive Virtual Environments (FIVE): speculations on the role of presence in virtual environments. PRESENCE: Teleoperators and Virtual Environments 6, pg. 603–616.

Tse, T.K., Wong, K.A., Wong, K.F., 2005. The utilization of building information models in nD modelling: A study of data interfacing and adoption barriers. Journal of Information Technology in Construction 10, pg. 85–110.

Whisker, V.E., Baratta, A.J., Yerrapathruni, S., Messner, J.I., Shaw, T.S., Warren, M.E., Rotthoff, E.S., 2003. Using Immersive Virtual Environments to Develop and Visualize Construction Schedules for Advanced Nuclear Power Plants, in: Proceedings of ICAPP '03. Presented at the International Congress on Advances in Nuclear Power Plants, Cordoba, Spain, May 4-7, 2003.

Whyte, J., 2003. Innovation and Users: Virtual Reality in the Construction Sector. Construction Management and Economics 21, pg. 565–572.

Yessios, C.I., 1987. The Computability of Void Architectural Modeling, in: Kalay, Y.E. (Ed.), Principles of Computer-aided Design: Computability of Design. Wiley-Interscience, pg. 141–172.

Zikic, N., 2007. Evaluating Relative Impact of VR Components Screen size, Stereoscopy and Field of View on Spatial Comprehension and Presence in Architecture (M.S. Thesis). The Pennsylvania State University, University Park, PA.

INTEGRATED PROCESS MAPPING FOR BIM IMPLEMENATION IN GREEN BUILDING PROJECT DELIVERY

Wei Wu
Construction Management Program, California State University at Fresno, Fresno, California, USA

Raymond Issa
Rinker School of Building Construction, University of Florida, Gainesville, Florida, USA

ABSTRACT: *Professionals in the architecture, engineering and construction (AEC) industry are becoming more versed with building information modeling (BIM), and start to recognize its synergy with green building. As more owners are demanding better building performance to meet regulatory requirements, business goals or to establish a positive public image, implementing BIM in green building project delivery offers project teams the ideal leverage to meet owners' expectations. Current Green BIM practices are immature, ad-hoc and unsystematic. The lack of an integrated process is the biggest barrier to exploring the benefits of Green BIM to their full extent. The fact that most project teams are transient in nature also makes it challenging to replicate success from one project to another. Other major obstacles reside in understanding the subtleties in differentiating the roles and responsibilities of team members, determining appropriate BIM execution strategies and standardizing information exchange (IE). Hence, the purpose of this research is to conduct a comprehensive review of existing Green BIM strategies and best practices, and to develop an Integrated Green BIM Process Map (IGBPM) to provide guidance on BIM implementation in green building project delivery. The deliverables of this research include a customized worksheet for project sustainability goals and BIM use identification, Level 1 of the IGBPM and several examples of the Level 2 process maps using LEED as a use case. The IGBPM is valuable to industry practitioners since it represents a holistic and systematic approach to efficiently utilize limited BIM resources to overcome the challenges and complexities to successfully delivering the project and achieving the targeted green certification. The structural transparency of the IGBPM also encourages risk/benefit sharing that can help enhance collaboration among team members and eventually facilitate a more integrated delivery of green building projects.*

KEYWORDS: *Building information modeling, green building, process mapping, project delivery.*

1. INTRODUCTION

As BIM and green building both continue to gain momentum, more industry firms are embarking on Green BIM practices, which is an emerging trend in the architecture, engineering and construction (AEC) industry that leverages BIM in green building project delivery and attempts to capitalize on synergies between the two. For the time being, however, only a fraction of firms are knowledgeable about Green BIM, and an even smaller proportion of those firms are able to reap the full potential of what BIM offers for green projects (McGraw-Hill Construction 2010). Most firms are inexperienced and remain vigilant for empirical evidence and hard project data before taking any further steps. The market transformations for green building and BIM are subject to obstacles and uncertainties as commonly seen amid new technology absorption, and will need further stakeholder buy-in. Firms that refuse to use BIM in green building projects contend that BIM is still an evolving technology and has limited functionality. They feel BIM tools and models are too complicated to use, so they are better off relying on existing non-BIM tools that they are comfortable with (McGraw-Hill Construction 2010). Owners are hesitant to procure BIM services to avoid cost inflation and stay away from risks associated with an unfamiliar BIM workflow. Industry players often solely focus on the technical aspects of BIM implementation while overlooking the process aspects. They treat BIM as a technology add-on while eluding the efforts in adapting their business operation to accommodate the necessary organizational change and cultural transition when adopting BIM. Such tactics have seriously undermined the synergies between BIM and green building. As a result, existing Green BIM practices are usually immature, ad-hoc and unsystematic. The success of individual Green BIM project usually relies on the improvisations of a highly competent project team instead of deliberations based upon a well-thought-out, transferable BIM-integration process. Due to the transient nature of project team composition on construction projects, such success is difficult for the peer project teams to replicate. Opportunities are also lost in reinforcing and advancing the information and knowledge of Green BIM practices gained from previous projects. To reduce

---

Citation: Wu, W. & Issa, R. (2013). Integrated process mapping for BIM implemenation in green building project delivery. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

the hindrances of adopting new technology like BIM in green building, Häkkinen and Belloni (2011) suggested the necessity of learning what kind of decision-making phases, new tasks, actors, roles and ways of networking are needed. This encompasses understanding the subtleties in differentiating the roles and responsibilities of team members, determining appropriate BIM execution strategies and standardizing information exchange (IE) along with the green building project delivery process.

This research is a response to the need for a better, integrated process of implementing BIM in green building project delivery that project teams can count upon to capitalize on synergies between BIM and green building. An integrated process map of Green BIM practices, the *Integrated Green BIM Process Map* (IGBPM), was created using Business Process Model and Notation (BPMN), based upon the convergence of existing process models for green building project delivery and BIM execution. The scope of this research is limited to *Level 1: Overall Green BIM Process Map* and some example of *Level 2: Detailed Green BIM Process Maps with LEED as a Use Case*. The whole set of process maps, once completed, will offer a comprehensive and transferrable guide to project teams for planning and executing Green BIM practices. The positive impacts of process mapping on transparency encourage risk/benefit sharing, promote enhanced collaboration among team members and eventually facilitate the integrated delivery of green building projects.

2. BACKGROUND

This research is conducted on the basis of existing process modeling efforts in green building project delivery and BIM execution, initiatives and best practices of Green BIM implementation in industry, and cutting-edge research discoveries in academia on synergies of BIM and green building.

2.1 Green building project delivery process modeling

In this study, green building is defined as a construction project that is either certified under a recognized global green rating system (e.g. LEED, BREEAM and Green Globes) or built to qualify for certification (McGraw-Hill Construction 2013). This working definition fits best in the context of the business case for green building. In industry and academia, high performance building or sustainable building are often used interchangeably with green building, regardless of the differences between them.

Horman et al. (2004) have demonstrated that process plays a key role in successfully delivering a high performance green facility within budget and on time. The theory underpinning high performance project delivery is that reduced process waste is able to enhance both sustainable outcomes and the business case for sustainability (Horman et al. 2006). The optimal delivery processes for green buildings are not the same as those for traditional buildings. The integrated project delivery (IPD) method has caught a lot of attention in the industry and is considered superior to traditional processes. Process modeling is the critical first step to better understand the green building delivery processes (Klotz et al. 2007). Building process models emphasize important information, relationships and/or elements concerning the provision of the facility. The essences of the building process models are the steps of "how" the facility is constructed and "who" provides the necessary competencies to do so. A process model provides the basis for developing important understanding about the characteristics of high performance building delivery (Horman et al. 2006).

The Integrated Building Process Model (IBPM) developed by Sanvido (1990) using the IDEF0 modeling language was by far the most comprehensive of the models available to map a facility delivery process from inception to turnover. It has been the foundation for extensive research into how projects are completed. The IBPM was later on adapted and further developed with the additional elements needed for understanding high performance building project processes, such as the IBPM for High Performance Buildings ($IBPM^{HP}$) and the Integrated Design Process Model for High Performance Buildings ($IDPM^{HP}$) (Korkmaz et al. 2010). "Lean" (e.g. Klotz et al. 2007) and "system engineering" (e.g. Bersson 2012) principles have also been incorporated in popular innovations in process modeling. A significant proportion of literature on green building project delivery process modeling has chosen LEED certified buildings as case studies and frequently involved the use of BIM in LEED oriented design optimization and performance simulation. However, these process models have seldom addressed the impacts and implications of BIM implementation on LEED project delivery.

2.2 BIM project execution process modeling

Implementation of BIM on construction projects necessitates greater collaboration and integrated project delivery, and requires dramatic changes in current construction business practices. This is a significant challenge to the AEC industry considering the inherent fragmentation in the overall supply chain (NIBS 2007). Discrepancies in the BIM sophistication of project team members (Wix 2007) and the IE related interoperability issues (Gallaher et al. 2004) due to the heterogeneity of BIM software applications add extra dimensions of complexity to BIM project execution. The question of what is the best method of adopting BIM has not yet been answered (Coates et al. 2010), and consequently very few projects have been able to utilize the benefits of BIM to their full extent.

The key will be the integration of the BIM process. Conventional process models such as the IPBM (Sanvido 1990) typically represent the information that is not adequate for supporting the strategic decisions to be made by a construction team since an information handover is required encompassing many specific BIM tasks, company information and other external information. The desired process representation will need to address information including: the logical sequence and interdependency of the activities in the project delivery; the inputs, i.e., the Reference Information and BIM deliverables that support the activities within the process; the BIM outputs and the IE between processes; and the team participants or the agents responsible for a particular BIM task (Saluja 2009).

The BIM Project Execution Planning Guide (PEPG) (CIC 2010) provided the first well-formatted process model for BIM implementation at the project level. It defined the appropriate uses for BIM on a project (e.g., design authoring, cost estimating, and design coordination), along with a detailed design and documentation of the process for executing BIM throughout a project's lifecycle. Major contributions of this guide to facilitate better integrated BIM process in project execution include: a method to identify BIM Uses; a procedure for designing the BIM Process for the project; a method for defining the IE Requirements; a method to define the infrastructure necessary to support the BIM Process; a structured method for team implementation of the procedure through a series of meetings and intermediate tasks; and a structured method for individual organizational development of typical methods for BIM implementation.

As one of the underpinnings to an integrated BIM process, IE poses the biggest challenge to BIM practitioners. The Industry Foundation Classes (IFC) has become the interoperable standard for the exchange of building product information, with key enhancements from the Information Delivery Manuals (IDM) and Model View Definitions (MVD) (Eastman 1999). Significant progress has been made in the industry on advocating the IFC/IDM/MVD framework as the open IE standard for BIM execution, despite some of the recognized deficiencies. Eastman et al. (2009) and Panushev et al. (2010) have provided case studies of IE standardization in process modeling for precast/prestressed concrete using this framework. The Architecture, Engineering, Construction, Owner Operator Phase 1 (AECOO-1) Joint Testbed was another epic effort in developing and implementing IDM/MVD based methods to streamline communications between parties in the conceptual design phase to get an early understanding of the tradeoffs between construction cost and energy efficiency (OGC 2010).

2.3 State-of-the-art Green BIM practice and research

The 2010 SmartMarket Report by McGraw-Hill Construction offered a good summary of the cutting-edge strategies and approaches of Green BIM practices (McGraw-Hill Construction 2010). Accompanying the strong market momentum are strong governmental involvements in Green BIM. For instance, in the US, the General Service Administration (GSA) is leading the efforts to leverage BIM for high performance buildings, by establishing the National 3D-4D BIM program and publishing the BIM Guide Series (GSA 2012). In Europe, the 7th Framework Program (FP7) has produced research such as the energy-enhanced BIM (eeBIM) framework, an open and extensible mechanism to support the data flows for energy efficient design and lifecycle management (Katranuschkov et al. 2011).

In academia, there is a good diversity of scholarly research on BIM and green building design and construction, such as BIM for energy and thermal simulation (e.g. Schlueter and Thesseling 2008), lighting simulation (e.g. Huang et al. 2008), and daylighting simulation (e.g. Welle et al. 2012). There is also an interest on BIM-based building evaluation, e.g. Motawa and Carter (2012). With LEED being a globally-recognized green building rating system, BIM implementation in LEED oriented design, simulation, analysis and certification have caught a lot of attention in the research community. Many researchers have addressed the synergies between BIM and LEED. For instance, Biswas et al. (2008) and Wu and Issa (2010a) proposed system level integration of BIM and LEED; Barnes and Castro-Lacouture (2009) and Bank et al. (2010) demonstrated the possibilities of using BIM as a sustainable design decision-making tool, and relying on BIM-based information for LEED points calculation. In addition, O'Keeffe et al. (2009), Azhar et al. (2010), and Wu and Issa (2010b) looked at how BIM could facilitate the LEED certification process with design analysis optimization, information management, documentation generation and certification review. Finally, Wu and Issa (2011, 2012) proposed a cloud-BIM based framework to automate the LEED certification process.

3. METHODOLOGY

3.1 Process mapping methods and procedures

3.1.1 Preparatory tasks

Before conducting the actual process mapping, there are a few preparatory tasks to be completed. This will include the identification of key project stages, project participants, project sustainability goals, and the intended BIM uses to achieve these goals. As concluded from the literature review, IPD is preferred to traditional process in delivering *Green BIM* project. In practice, IPD exhibits fundamental differences from traditional project delivery methods in two primary areas: team assembly and project phasing/execution. It is critical to build an integrated team by: 1) identifying participant's roles at the earliest possible time; 2) pre-qualifying team members; 3) encouraging broad involvement of stakeholders interests groups; 4) defining consensus-based goals and values; 5) aligning organizational and business structure with needs and constraints; and 6) developing agreements on roles and accountability, risks and benefits. IPD redefines project phases into *Conceptualization, Criteria Design, Detailed Design, Implementation Documents, Agency Coordination/Final Buyout* and *Construction,* which enables the integration of early input from constructors, installers, fabricators and suppliers as well as from designers, and the ability to model and simulate the project accurately using BIM tools (AIA 2007). The project sustainability goals, which are directly linked with the primary responsibilities of team participants and expected green building project outcomes, should be determined by the owner's commitment, the allowed time and budget, the project team competency and other contributing factors. Most green building rating systems are prescriptive and offer pre-defined criteria (in both mandatory and optional formats) for desired building features, including site selection, orientation, energy efficiency, water consumption, material reuse and localization, daylighting and open view design, indoor air quality and so on. The overall certification level will be based upon the total points scored in meeting these criteria. Therefore, strategizing the certification approach using these criteria as references is at the heart of the preparatory tasks, and significantly affects the selection of team participants and BIM uses.

3.1.2 Process mapping

Upon the completion of preparatory tasks, the process map of *Green BIM* was created using BPMN in Microsoft Visio. BPMN is a popular process modeling standard and graphical representation specifying business processes. Recently its use was mandated by the National BIM Standard effort commissioned by the National Institute of Building Science (NIBS). BPMN offers simple yet standardized visual communication to users to understand the external and internal business procedures through a business process diagram. BPMN is especially attractive to the BIM/IFC researchers since it offers better integration with the detailed information exchange mapping initiatives used in the IDMs currently being developed for the NBIMS as well as BIM Standards in other countries. The process maps created in this research are limited to: *Level 1: Overall Green BIM Process Map* and several examples of *Level 2: Detailed Green BIM Process Maps with LEED as a Use Case*.

3.2 LEED as a Use Case

The proposed process maps were intended to assist project teams in achieving a certain type of green building certification with integrated, process-driven Green BIM practices. The literature review has justified the selection of LEED as a use case due to its significant market share in the North American green building market and a global recognition as one of the most popular green building rating systems. LEED has been developed into a portfolio of rating systems for various types of buildings with several versions. This research chose LEED for New Construction 2009 (LEED-NC 2009), which had the most registered projects pursuing its certification in the LEED portfolio. When developing the Level 2 process maps, the LEED criteria (i.e. the LEED credit requirements) have been taken into account, either as reference information to a particular task in the process map, or as an input to "what-if" scenario analysis. Some of the IE incidences that took place along the process map were also LEED-dedicated. For instance, at the end of certain tasks/events in the process map, there might be information generated that could be plugged into the required LEED documentation. With LEED as a use case, it became much easier to show how the Green BIM process differs from a generic BIM execution process, and how the project team needs better collaboration to streamline the exchange and synthesis of domain-specific information, yield the desired project performance outcomes and achieve the desired green building certification.

4. RESULTS

4.1 Preparatory tasks outcome

IPD is the preferred project delivery method for green building projects and BIM implementation, and was selected in this research. IPD is also representative of the other major delivery methods, which increases the usability of the process maps developed in this study. One of the major features of IPD is that it encourages early involvement of stakeholders and encourages concurrent activities and enhanced collaboration among project participants. The identified project phases include: *Conceptualization, Criteria Design, Detailed Design, Implementation Documents, Agency Coordination/Buyout, Construction* and *Post-Construction*. The major project participants include: *Owner, Architect* (expandable to include *Landscape Architect*) *Engineer* (expandable to specify *Civil, Mechanical, Electrical, Structural,* etc.), *Contractor, Commissioning Agent* (*CxA*), *Consultant* (including *LEED Administrator*), *Trade Contractor* (expandable to *M/E/P,* etc.), and *Suppliers*.

To identify the sustainability goals of the project, it is important to refer to the green building rating system under which the project is pursuing certification. To give a meaningful example, LEED-NC 2009 was used here to demonstrate the steps followed and proved to be a great tool to accomplish this task. As shown in Fig. 1 (the view is cropped due to overall large size), the *LEED Goal-BIM Use Identification Worksheet* was developed based on the LEED-NC 2009 Checklist/Scorecard. Usually a LEED project will start with the process called "LEED Charrette", which is a type of workshop where project participants indulge in brainstorming, discussion, and strategy development to create a shared vision. Participants in these workshops usually include the owner, architect, consultants, contractors, landscape architect, and commissioning agents. The outcome of the Charrette includes a first draft of the LEED scorecard, a preliminary rating, and defining the roles of each member of the project team. The *LEED Goal-BIM Use Identification Worksheet* used a LEED scorecard came from a Charrette of the new Biological Science Building at Georgia Southern University that is pursuing LEED-NC Silver and currently under construction. The worksheet clearly indicates the attempted LEED credits, the total points achievable, and the responsible parties for each credit. The LEED scorecard was customized to facilitate the identification of the potential BIM uses. Following the methodology recommended by CIC (2010), BIM uses were focused to meeting the requirements of these targeted LEED points, which were stipulated with more details and recommended strategies in the LEED reference guide (USGBC 2009).

LEED 2009 for New Construction and Major Renovations
Project Checklist

Biological Science Building
1-Nov-10

50	29	31	D/C	Total Project Score		Achieved Points: 50	Responsibility		BIM Use	Value to Project (High/Med/Low)	Capability Rating (High/Med/Low) R C E	Notes	Proceed with Use (Yes/No/Maybe)
16	3	7		**Sustainable Sites**		Possible Points: 26	**Responsibility**						
Y	?	N	D/C				Main	Secondary					
Y			C	Prereq 1	Construction Activity Pollution Prevention		CE		Site Utilization Planning				Yes
								GC	Site Utilization Planning				
		1	D	Credit 1	Site Selection	1	CE		Site Analysis				No
		5	D	Credit 2	Development Density and Community Connectivity	5	LEED-AD		Site Analysis				No
		1	D	Credit 3	Brownfield Redevelopment	1	CE		Site Analysis				No
6			D	Credit 4.1	Alternative Transportation—Public Transportation Access	6	LEED-AD		Site Analysis				Yes
1			D	Credit 4.2	Alternative Transportation—Bicycle Storage and Changing Rooms	1	ARCH		Site Analysis				Yes
3			D	Credit 4.3	Alternative Transportation—Low-Emitting and Fuel-Efficient Vehicles	3	ARCH		Site Analysis				Yes
2			D	Credit 4.4	Alternative Transportation—Parking Capacity	2	ARCH		Site Analysis				Yes
1			C	Credit 5.1	Site Development—Protect or Restore Habitat	1	LARCH		Site Utilization Planning				Yes
								GC	Site Utilization Planning				
	1		D	Credit 5.2	Site Development—Maximize Open Space	1	CE		Site Analysis				Maybe
	1		D	Credit 6.1	Stormwater Design—Quantity Control	1	CE		Site Analysis				Maybe
1			D	Credit 6.2	Stormwater Design—Quality Control	1	CE		Site Analysis				Yes
1			C	Credit 7.1	Heat Island Effect—Non-roof	1	ARCH		Site Utilization Planning				Yes
								LARCH	Site Utilization Planning			For Option 1	
	1		D	Credit 7.2	Heat Island Effect—Roof	1	ARCH		Design Review			Check SRI	Maybe
								SE	Egineering Analysis			For Option 2	
1			D	Credit 8	Light Pollution Reduction	1	EE		Lighting Analysis				Yes
7	3	0		**Water Efficiency**		Possible Points: 10	**Responsibility**						
Y	?	N					Main	Secondary					
Y			D	Prereq 1	Water Use Reduction—20% Reduction		LEED-AD		Design Review				Yes
								ME	Mechanical Analysis				
4			D	Credit 1	Water Efficient Landscaping	2 to 4	LARCH		Site Analysis				Yes
					Reduce by 50%	2							Yes
					No Potable Water Use or Irrigation	4							Yes
	2		D	Credit 2	Innovative Wastewater Technologies	2	LEED-AD		Sustainability Evaluation				Maybe
								ME	Mechanical Analysis				
3	1		D	Credit 3	Water Use Reduction	2 to 4	LEED-AD		Sustainability Evaluation				Yes
					Reduce by 30%	2		ME	Mechanical Analysis				Yes
					Reduce by 35%	3							Yes
					Reduce by 40%	4							Maybe
5	13	17		**Energy and Atmosphere**		Possible Points: 35	**Responsibility**						
Y	?	N					Main	Secondary					
Y			C	Prereq 1	Fundamental Commissioning of Building Energy Systems		CxA		Asset Management				Yes
									Building System Analysis				
									Building Maintenance Scheduling				
								TC	3D Coordination				
								GC	Phase Planning				
Y			D	Prereq 2	Minimum Energy Performance		LEED-AD		Energy Analysis				Yes
								CONS	Energy Analysis			Energy Simulation	
								ME	Mechanical Analysis			Space, Zone, Load	
Y			D	Prereq 3	Fundamental Refrigerant Management		ME		Mechanical Analysis				Yes
5	5	9	D	Credit 1	Optimize Energy Performance	1 to 19	LEED-AD		Energy Analysis				Yes
					Improve by 12% for New Buildings or 8% for Existing Building Renovations	1		CONS	Energy Analysis			Energy Simulation	Yes
					Improve by 14% for New Buildings or 10% for Existing Building Renovations	2		ME	Mechanical Analysis			Space, Zone, Load	Yes
					Improve by 16% for New Buildings or 12% for Existing Building Renovations	3							Yes
					Improve by 18% for New Buildings or 14% for Existing Building Renovations	4							Yes
					Improve by 20% for New Buildings or 16% for Existing Building Renovations	5							Yes
					Improve by 22% for New Buildings or 18% for Existing Building Renovations	6							Maybe
					Improve by 24% for New Buildings or 20% for Existing Building Renovations	7							Maybe

Fig. 1: LEED Goal - BIM Use Identification Worksheet (cropped view).

4.2 Process Mapping – Level 1

Process mapping using BPMN was fairly straightforward, and the Microsoft Visio streamlined the efforts. The basic steps of creating *Level 1: Overall Integrated Green BIM Process Map (IGBPM)* included: defining the each process of specific *Green BIM* practice per project delivery stage; allocating potential BIM uses in this process; designating the responsible party; specifying the process input and output, and necessary Level 2 processes; and repeating similar steps to map the rest of the process between the process Start and End. The resulting Level 1 process map is partially shown in Fig. 2 (due to its size). The upper swimlane shows all BIM uses over the integrated Green BIM project delivery. The lower swimlane illustrates the incidences of IE and various inputs/outputs generated along with process progression. Some of the IE incidences were highlighted because they represented a specific LEED deliverable that could be used to prepare relevant LEED documentation for certification review purposes. This Level 1 process map was developed based upon the BIM PEPG (CIC 2010) and the LEED-NC 2009 rating system. In comparison with the Level 1 process map in the BIM PEPG, it has a lot more BIM uses up front. As mentioned previously, this is due to the fact that IPD encourages early involvement of stakeholders, and a lot of concurrent activities are taking place at the early stage of the project delivery process.

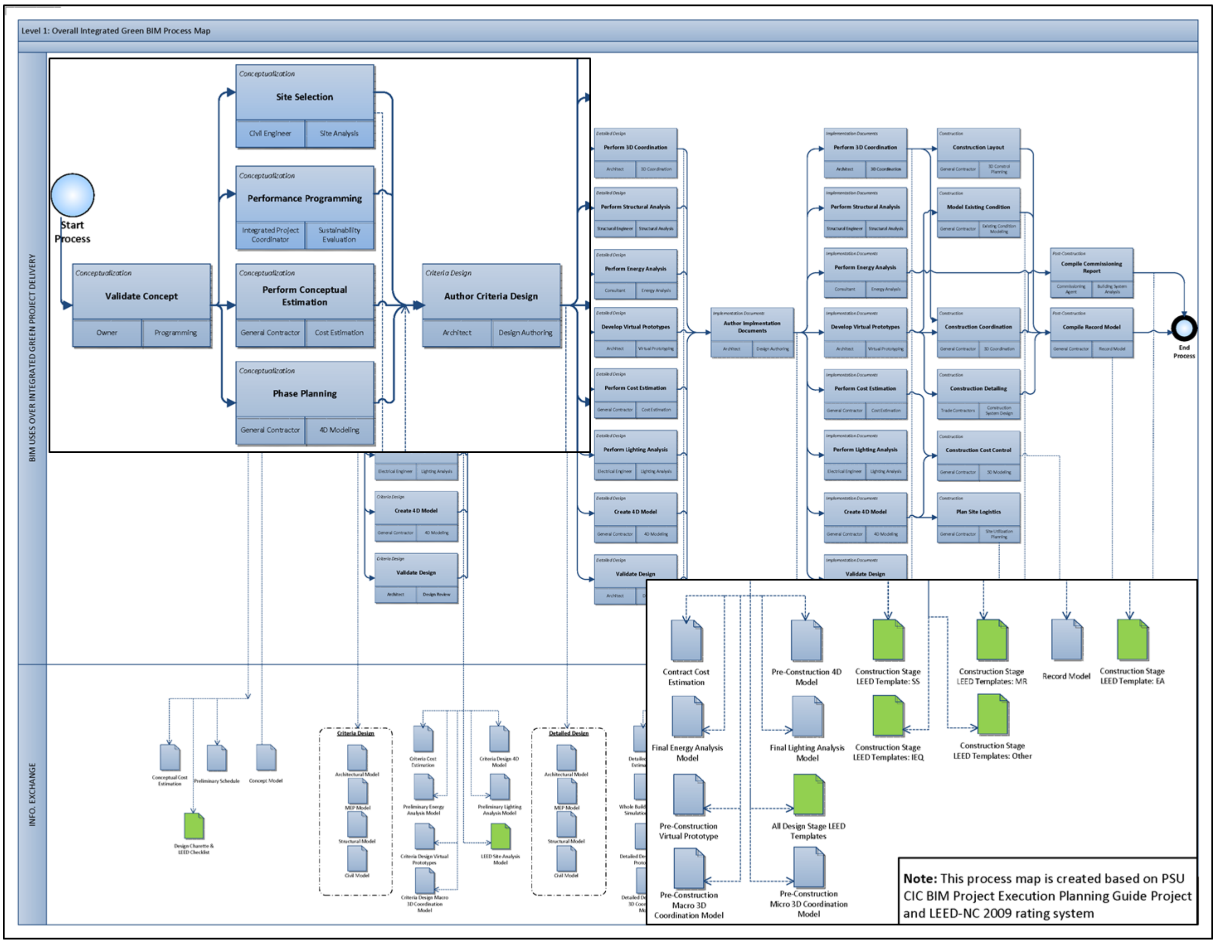


Fig. 2: Level 1 Process Map: Overall Integrated Green BIM Process Map (IGBPM) (partially enlarged).

4.3 Process Mapping – Level 2

The complete set of Level 2 process maps is still an ongoing effort. Some sample process maps, the *Level 2 Process Maps: Site Analysis* and *Energy Analysis with LEED as a Use Case* was exhibited here in Figs. 3-4 as examples. As noted, the Level 2 process map examples were also developed based on the current efforts of OGC AECOO-1 Joint Testbed (OGC 2010), BIM PEPG (CIC 2010) and the LEED-NC 2009 rating system. Using a similar methodology, other Level 2 process maps can be developed to incorporate the green recipes such as LEED criteria along the integrated green building project delivery.

Generally speaking, the differences between the IGBPM Level 2 process maps and the ones developed by CIC (2010) reside in how the prescribed green criteria, or the LEED credits requirements in the use case, influence the BIM uses planning and execution. This influence also occurs in different manners. For instance, a LEED credit requirement might offer extra information for performing a task/event in the process. In this case, it is a piece of "REFERENCE INFO.", located at the uppermost swimlane of the Level 2 process maps. A LEED credit requirement may also show up in the middle "PROCESS" swimlane and directly impact the process by necessitating a "what-if" scenario analysis, as where the "LEED Gateway" (the Yes/No gateway in green color) is shown in Figs. 3-4. It engenders extra sub-processes in the process map, when the team decided to evaluate the feasibility of achieving these LEED points. A third circumstance of the LEED influence is when an incidence of IE generates a piece of information that becomes part of the LEED documentation, shown as process deliverables in the lowest "INFO. EXCHANGE" swimlane. To be specific, in Fig. 3, the *Level 2 Process Map: Site Analysis with LEED as a Use Case* enables "what-if" scenario analysis to encourage the developer to select the project site with development density and neighborhood connectivity in mind. The parking capacity requirements of LEED SS credits also attempt to reduce unnecessary hardscapes due to the construction of excessive parking lots. Fig. 4 exemplifies the BIM-based energy analysis process in a LEED project when the project team decides to go for the whole building energy simulation option. This option is the most challenging one but it could earn the most LEED points as needed for the certification. In a generic Level 2 Energy Analysis process map, it does not specify the base condition and the reference standards (e.g., ANSI/ASHRAE/IESNA 90.1-2007) that the energy analysis should follow. In contrast, the Level 2 Process Map: Energy Analysis with LEED as a Use Case did specify all these premises and requirements, which apparently better advises the project team on appropriately conducting the desired whole building energy simulation.

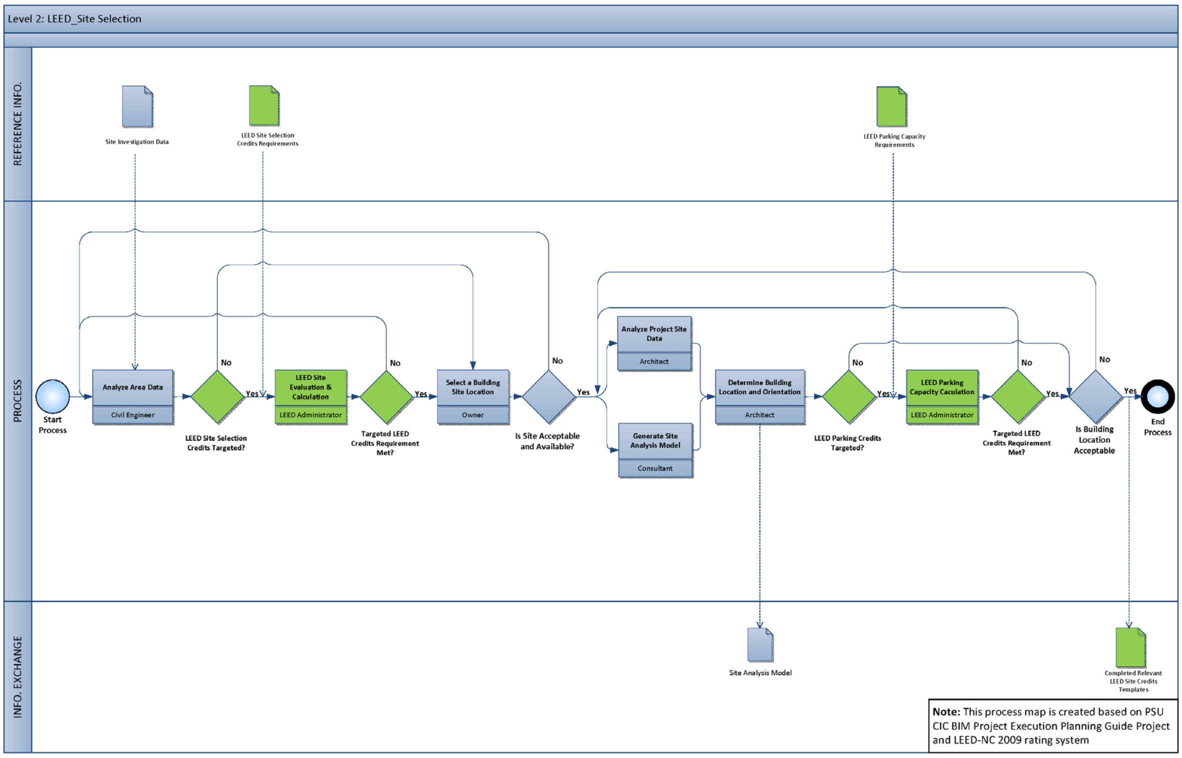


Fig. 3: Level 2 Process Map: Site Analysis with LEED as a Use Case.

5. CONCLUSIONS

In conclusion, this research investigated a critical issue in promoting Green BIM practice in the AEC industry, which is the need for an integrated process. Project teams have been struggling to capitalize on the synergies between BIM and green building to the full extent, due to the immature, ad-hoc and unsystematic practices. This is frustrating and can be avoided with the availability of better guidelines. Existing efforts on process modeling for both green building and BIM execution have laid a solid foundation for this research to take one step further, and create an Integrated Green BIM Process Map (IGBPM). The strengths of the proposed IGBPM include:

- The clear identification of sustainability goals, corresponding BIM uses, and the responsible parties without too much extra efforts compared with the typical green building project delivery.
- The Level 1 process map provides an overall roadmap to plan for Green BIM practices early on in the project delivery stage, which adds value to the project, and reduces uncertainty and risks.
- The Level 2 process maps offer step-by-step operational guidance on detailed execution of specific Green BIM practices. It ensures that the right tools, desired resources and competent personnel will be mobilized to perform the tasks. The anticipated process outcomes and IE/ER are well understood by all project participants, which will significantly improve productivity and reduce the costs associated with interoperability issues.

- The IGBPM was designed with transferability in mind, which makes it easily customizable to any project delivery method in pursuit of any green building certification.

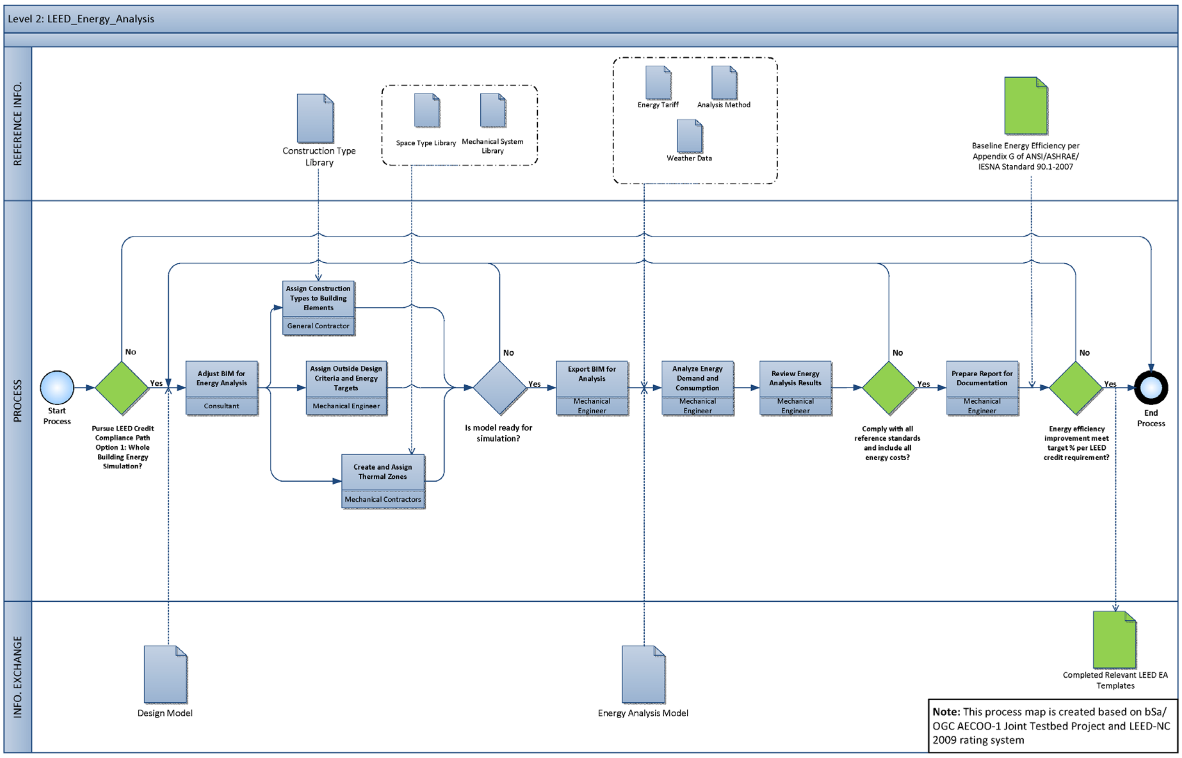


Fig. 4: Level 2 Process Map: Energy Analysis with LEED as a Use Case.

However, there are limitations to this research and the proposed IGBPM. At this moment, the IGBPM is not a finished product. Most Level 2 process maps, IE and ER are still under development. Another major weakness is that the IGBPM has not been validated with actual Green BIM projects. Some preliminary validation has been attempted with the Biological Science Building on Georgia Southern campus. The developed process maps were originally planned to be validated through this case study. Nevertheless, after the preparatory tasks were performed based on the information from this project, a conversation with the GC revealed that the design-stage BIM models were never further developed with construction details and thus were rarely used during the construction process. As a result, the process maps have not gone through any comprehensive validation yet.

Meanwhile, from a research perspective, there are still broad concerns regarding BIM contracting, and the lack of an adequate understanding of the IPD method. In order to achieve the expected outcomes of implementing the IGBPM, relationship building and collaborative project management are indispensable, since they are the supporting infrastructure for integrated Green BIM practices.

Further development of the IGBPM will be looking at the Open BIM initiative and how the IFC/IDM/MVD framework will influence Green BIM practices, and the impact on its development due to the use of open standards for information exchange under this framework. In closing, it is encouraging to observe that the BPMN standard provides good integration with IFC, and more BIM software vendors are embracing IFC as a standard for BIM information exchange.

6. REFERENCES

AIA. (2007). Integrated Project Delivery: A Guide. The American Institute of Architects, <http://www.aia.org/contractdocs/AIAS077630> (Mar. 1, 2013).

Azhar S., Carlton W., Olsen D. and Ahmad I. (2010). Building information modeling for sustainable design and LEED rating analysis, *Automation in Construction*, Vol. 20, No. 2, 217-224.

Barnes S. and Castro-Lacouture D. (2009). BIM-enabled Integrated Optimization Tool for LEED Decisions, *Proceedings of 2009 International Workshop on Computing in Civil Engineering*, ASCE, June 24-27, Austin, TX, 258-268.

Bersson T.F. (2012). A Framework for Application of System Engineering Process Models to Sustainable Design of High Performance Buildings, Dissertation, George Washington University, Washington, D.C.

Biswas T., Wang T.H. and Krishnamurti R. (2008). Integrating sustainable building rating systems with building information models, *Proceedings of 13th International Conference on Computer Aided Architectural Design Research in Asia*, April 9-12, Chiang Mai, Thailand, 193-200.

CIC. (2010). BIM Project Execution Planning Guide, Version 2.0, CIC Research Group, Pennsylvania State University, University Park, PA.

Coates P., Arayici Y., Koskela K., Kagioglou M., Usher C. and O'Reilly, K. (2010). The key performance indicators of the BIM implementation process, *Proceedings of the International Conference on Computing in Civil and Building Engineering* (Tizani W., editor), June 30 - July 2, Nottingham, UK.

Eastman C. M. (1999). Building product models: Computer environments supporting design and construction, CRC Press LLC, Boca Raton, FL.

Eastman C., Sacks R., Panushev I., Aram V. and Yagmur E. (2009). The National Building Information Modeling Standards - Information Delivery Manual for Precast Concrete, PCI-Charles Pankow Foundation, <http://dcom.arch.gatech.edu/pcibim/documents/IDM_for_Precast.pdf> (Mar. 01, 2013).

Gallaher M. P., O'Connor A. C., John L. Dettbarn J., and Gilday L. T. (2004). Cost analysis of inadequate interoperability in the U.S. capital facilities industry, GCR 04-867, August 2004, National Institute of Standards and Technology, Gaithersburg.

GSA. (2012). 3D-4D Building Information Modeling, General Service Administration, <http://www.gsa.gov/portal/content/105075> (Mar. 01, 2013).

Häkkinen T. and Bellon, K. (2011). Barriers and drivers for sustainable building, *Building Research & Information*, Vol. 39, No. 3, 239–255.

Horman M. J., Riley D.R., Pulaski M. H. and Leyenberger C. (2004). Lean and Green: Integrating Sustainability and Lean Construction, *Proceedings of CIB World Building Congress*, May 1-7, Toronto, Canada.

Horman M.J., Riley D.R., Lapinski A.R., Korkmaz S., Pulaski M.H., Magent C., Luo Y., Harding N. and Dahl P.K. (2006). Delivering green buildings: process improvements for sustainable construction, *Journal of Green Building*, Vol. 1, No. 1, 123–140.

Huang Y. C., Lam K. P. and Dobbs G. (2008). A scalable lighting simulation tool for integrated building design, *Proceedings of the 3rd National Conference of IBPSA-USA*, July 30 – August 1, Berkeley, California.

Katranuschkov P., Guruz R., Liebich T. and Bort B. (2011). Requirements and Gap Analysis for BIM Extension to an Energy Enhanced BIM Framework, *Proceedings of the 2nd Workshop of eeBuilding Data Models*, October 26 – 28, Sophia Antipolis, France.

Klotz L., Horman M. and Bodenschatz M. (2007). A Lean Modeling Protocol for Evaluating Green Project Delivery, *Lean Construction Journal*, Vol. 3, No. 1, 1-18.

Korkmaz S., Messner J., Riley D.R. and Magent C. (2010). High-Performance Green Building Design Process Modeling and Integrated Use of Visualization Tools, *Journal of Architectural Engineering*, Vol. 16, No. 1, 37–45.

McGraw-Hill Construction. (2010). Green BIM: How Building Information Modeling is Contributing to Green Design and Construction, McGraw-Hill Construction, Bedford, MA.

McGraw-Hill Construction. (2013). World Green Building Trends: Business Benefits Driving New and Retrofit Market Opportunities in Over 60 Countries, McGraw-Hill Construction, Bedford, MA.

Motawa I. and Carter K. (2013). Sustainable BIM-based Evaluation of Buildings, *Procedia – Social and Behavioral Sciences*, Vol. 74, 116-125.

NIBS. (2007). United States National Building Information Modeling Standard Version 1 – Part 1: Overview, Principles and Methodologies, Whole Building Design Guide, <http://www.wbdg.org/pdfs/NBIMSv1_p1.pdf> (Mar. 1, 2013).

OGC. (2010). Summary of the Architecture, Engineering, Construction, Owner Operator Phase 1 (AECOO-1) Joint Testbed, buildingSMART alliance (bSa) and the Open Geospatial Consortium, Inc. (OGC), <http://projects.buildingsmartalliance.org/files/?artifact_id=2754> (Mar. 01, 2013).

Panushev I., Eastman C., Sacks R., Venugopal M. and Aram V. (2010). Development of the National BIM Standard for Precast/Prestressed Concrete, *Proceedings of CIB W78 27th International Conference*, November 16-18, Cairo, Egypt.

Saluja C. (2009). A Process Mapping Procedure for Planning Building Information Modeling (BIM) Execution on a Building Construction Project, Master Thesis, Pennsylvania State University, University Park, PA.

Sanvido V. E. (1990). An integrated building process model, Computer Integrated Construction Research Program Technical Report #1, Pennsylvania State University, University Park, PA.

Schlueter A. and Thesseling F. (2009). Building information model based energy/exergy performance assessment in early design stages, *Automation in Construction*, Vol. 18, No. 2, 153-163.

USGBC. (2009). LEED Reference Guide for Green Building Design and Construction, US Green Building Council, Washington, D.C.

Welle, B., Rogers, Z., and Fischer, M. (2012). "BIM-Centric Daylight Profiler for Simulation (BDP4SIM): A methodology for automated product model decomposition and recomposition for climate-based daylighting simulation." Building and Environment, 58, 114-134.

Wix J. (2007). Information Delivery Manual: Guide to components and development methods, buildingSMART, <http://iug.buildingsmart.org/idms/development/IDMC_004_1_2.pdf/view> (Mar. 01, 2013).

Wu W. and Issa R.R.A. (2010a). Application of VDC in LEED projects: framework and implementation strategy, *Proceedings of CIB W78 27th International Conference on IT in Construction*, November 15-19, Cairo, Egypt.

Wu W. and Issa R.R.A. (2010b). Feasibility of integrating building information modeling and LEED certification process, *Proceedings of the International Conference on Computing in Civil and Building Engineering* (Tizani W., editor), June 30 - July 2, Nottingham, UK.

Wu W. and Issa R.R.A. (2011). BIM Facilitated Web Service for LEED Automation, *Proceedings of 2011 ASCE International Workshop of Computing in Civil Engineering*, June19-22, Miami, Florida, ASCE, 673-681.

Wu W. and Issa R.R.A. (2012). Leveraging Cloud-BIM for LEED Automation, *Journal of Information Technology in Construction*, Vol. 17, 367-385.

AUTOMATED SAFETY-IN-DESIGN RULE-CHECKING FOR CAPITAL FACILITY PROJECTS

Sijie Zhang & Jochen Teizer
RAPIDS Construction Safety and Technology Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA 30332-0355

Esau Perez & Michael McDonald
Chevron ETC, 3901 Briar Park, Houston, TX 77042

ABSTRACT: *Safety-in-design (SID) reviews are mandatory for capital facility projects because they eliminate hazards before activities in the construction, operation, and maintenance phases take place. Existing SID review processes which many large corporations have in place, however, still rely mainly on manual input and judgment of experienced safety experts. Often very skilled humans make decisions based upon paper-based drawings or three-dimensional visualization models. As such, tasks in safety-in-design review sessions remain to be manual and thus are very much time-consuming, expensive. Furthermore, if not all hazards are detected and mitigated, they can be potentially error-prone. Unsafe design ultimately exposes workers at risk as it provides an unsafe work environment. It can also become very costly if unsafe design is detected outside of the design and construction planning phases of a capital facility project.*

The objective of this work was to develop a safety code compliance checking technology that does not replace human judgment, but supports human decision making of safety experts, designers, engineers, and field staff. The developed work applies novel safety code compliance checking algorithms on intelligent information models which are prepared during design and construction planning. The initial scope of the developed algorithms is limited to check for safe work access and egress requirements in existing information models. As existing safety rules and best practices are embedded in the developed code compliance checking system, they can be automatically executed on information models which exist for every capital facility project. A case study is presented to illustrate its practical implementation for an off-shore oil platform. Results show that the developed system generates automated reports that list the safety violations and furthermore, along with visual screenshots of the unsafe object in the information model, indicate the process of how these issues can be mitigated based upon established best safety practices. The significance of human-assisted decision-making in SID reviews and its potential to lead to safer designs early in a project is explained.

KEYWORDS: *Capital facility projects, design for safety, design reviews, information modeling, rule checking, 3D model, safety-in-design.*

1. INTRODUCTION

Major capital facility projects typically involve a large number of organizations and individuals over a long lifecycle. They are often built across the globe, in different regions and under different cultural contexts. Such complex projects are furthermore driven by very tight schedules and have limited resources available. As a consequence, the responsibility of who designs, plans, reviews, manages, and controls safety becomes unclear. However, it remains essential that such projects are designed and built in a safe way; otherwise cost and time overruns occur when safety issues are embedded in faulty project design and move forward to detailed planning and ultimately construction, operation, and maintenance. Therefore, safety-in-design (SID) emerged as a concept of involving safety requirement and risk management knowledge into the project design phase. Its goal is to eliminate workplace incidents (e.g., accidents that lead to injuries and/or fatalities) and provide a safe workplace. Expected other benefits are reducing the likelihood of changes in the field and associated cost and time overruns.

Safety engineering integrates risk management principles into the design and construction planning when: (1) owner, contractor, and other relevant project stakeholders are involved in the decision-making process, (2) associated risks and hazards inherently embedded in a design are systematically identified and eliminated/mitigated, and (3) the entire project team communicates and solves residual risks associated with the design and construction plans. To adopt and implement elements of the SID process, a regulatory push towards SID was established in United Kingdom in 1995. It required designers to perform Construction Hazards Prevention

Citation: Zhang, S., Teizer, J., Perez, E. & McDonald, M. (2013). Automated safety-in-design rule-checking for capital facility projects. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

through Design (CHPtD). The approach was later adopted throughout the European Union. Australia has also moved towards mandating CHPtD practices and since then has demonstrated its leadership by making practical resources for designers and for CHPtD implementation available online (Toole and Gambatese 2008). The SID process has as such been detailed for application in the entire lifecycle of a project, including design, planning, construction, operation, maintenance, repair and demolition/refurbishment. Specifically, it is a designer's responsibility to prepare a safe design based upon understanding the range of work activities and work environment which are associated to building, maintaining, repairing, servicing, and cleaning a facility (Victoria 2005).

The current design review process in many capital facility projects, however, still relies mainly on safety expert opinions. These experts base their decision upon paper drawings or three-dimensional visualization models. Their task remains mostly manual and thus is very time-consuming, costly, and eventually error-prone. Proposed is an automated safe code compliance-checking system that supports humans in safety decision making early in a project phase by using intelligent information models.

2. BACKGROUND

2.1 Human factors engineering and requirements for a capital facility project

Human factors engineering is a multidisciplinary effort. It compiles and generates information about the capabilities and limitations of humans. It applies information to equipment, systems, facilities, procedures, environments, training, and personnel management to produce safe, comfortable, and effective human performance (Federal Aviation Administration 2005). When human factors is applied early in the acquisition process, it enhances the probability of increased performance, safety, and productivity; decreased lifecycle staffing and training costs; and becomes well-integrated into the program's strategy, planning, cost and schedule baselines, and technical tradeoffs. Otherwise, late changes in operational, maintenance or design concepts are expensive and involve high-risk program adjustments. For instance, design professionals need to provide adequate working distances in their designs for the various construction trades and common tools. An example inadequate clearance between steel bolts and adjacent steel members must be provided to allow the use of typical positioning and bolting or welding tools (Toole and Gambatese, 2008). Ergonomic issues may also be included in spatial considerations for constructability (Bello 2012). An alternative approach was developed by Gambatese and Hinze (1998) that focused on construction industry safety best practices as they relate to project-specific hazards.

2.2 Existing manual checking approach

Designers and construction planners are encouraged by most owners to specifically address worker safety in their work. Their involvement, however, has largely been a voluntary effort in the US (Gambatese and Hinze 1998). Another problem is that many times designers and planners have little to no background in safety rules and regulations, making it very difficult for them to apply advanced safety concepts or best safety practices in their work. For these reasons, Frijters and Swuste (2008) designed effective qualitative evaluation methods, e.g. panel discussions, which assist them in developing safer design alternatives and better construction methods. They also pointed out that administering such safety design review panels in practice is very resource intensive as it requires physical presence of many design, construction, and safety experts in one location and, depending on a project's size, for several days or even weeks.

The basic work flow of a SID implementation is illustrated in Figure 1. Since designers typically have very limited to no understanding of how their design influences construction and operational safety, owners provide SID training to all designers before the design phase starts. After the owner communicates the project objective and scope, designers create their first design of the facility. As the initial model of the design inherently includes unsafe design elements and other constructability issues, it is reviewed by the SID engineer for code compliance. Concurrently, construction experts look at constructability issues.

Communication of safety issues in the model review phase is mainly between the designers and SID engineers and through e-mail and conference calls. For that reason they frequently meet and review in teams. It is often the SID engineers who point out design flaws to the designers. Safety markups on two-dimensional drawings visualize the issues. These often do not explain clearly enough or solve issues as they relate to spatial constraints in a model. For many years 3D and information modeling have alleviated some of the visualization issues related to spatial objects. Clash detection tools in information modeling software has become one of the most popular applications as it automatically detects most the time and spatial conflicts. They often also indicate constructability issues, but may not provide methods on how they are solved. It is humans that then redesign the flawed model.

Sophisticated clash detection tools specifically for safety do not exist. As such, alternative design approaches that lead to a safer design are only then successfully integrated during the model review phase when a SID engineer detects a safety issue and points it out to a designer. It is then up to the designer resolving any such issue that originated from a mistake or flaw in the initial design. More importantly, mitigating unsafe design during model review ensures that less time and money is wasted downstream in the construction and operation phases. A model review session thus serves as an important and critical point in time for designing safer and more constructible models. The sooner it can be facilitated in the design process, the more efficient and effective will be the SID implementation workflow.

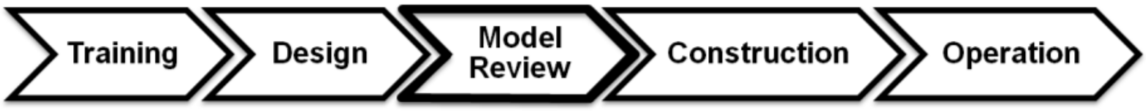


Fig. 1: SID implementation workflow.

2.3 3D information modeling for automate compliance checking

With the advance of visualization and information modeling technology, more and more attention has been put on checking the quality of design models. Existing commercial software such as Navisworks and Tekla BIMsight were designed for viewing 3D models and clash detection. Latter allows detecting clashes of objects as their spatial properties create a geometric conflict in a digital 3D model.

Zhang et al. (2013) developed the first safety-rule checking engine to detect and resolve fall-related safety hazards. Their work also estimates, visualizes, and schedules protective fall protection protective equipment in building information models (BIM). Building design code checking (Eastman et al. 2009) including circulation check (Lee et al. 2010) has also been explored. However, no existing application or research has been found on the topic of automated SID checking of design models.

3. RESEARCH METHODOLOGY

The developed safety code or rule-checking approach is illustrated in Figure 2 and further explained as follows:

(1) SID rule interpretation: An existing SID best practice, typically a text document with illustrations, is first examined and converted into a parameterized rule set. An example of the rule interpretation from (Chevron Corporation 2012) is shown in Table 1.

Table 1: Rule interpretation of SID rule of Main walkway.

Natural Language Rule	"Main walkway routes through plants, buildings, and topsides modules shall be a minimum clear width of 48 inches (1,219 mm)."

Interpreted rule	If (MainWalkway.Width >= 1219)
	Then pass;
	else
	fail;

(2) 3D model preparation: Before the start of the design model review process, the work of designers and engineers including MEP, structure, architectural from designers are typically integrated For the purpose of SID rule-checking, these model need to be prepared with correct geometry and attributes. The result is that the interpreted rule can be correctly mapped to the corresponding model object.

(3) Rule execution: The parameterized rules are applied to the geometry of the information model. The rule-checking is executed automatically on the entire model.

(4) Rule-checking reporting: The results of running the rule-checker are reported. Details are listed in a table format that is easy for humans to comprehend. The table contains the safety clash, the safety code or regulation that is violated, a visual snapshot of the 3D model objects or space that was violated, and finally and if available the recommended safety best practice on file to resolve the safety issue.

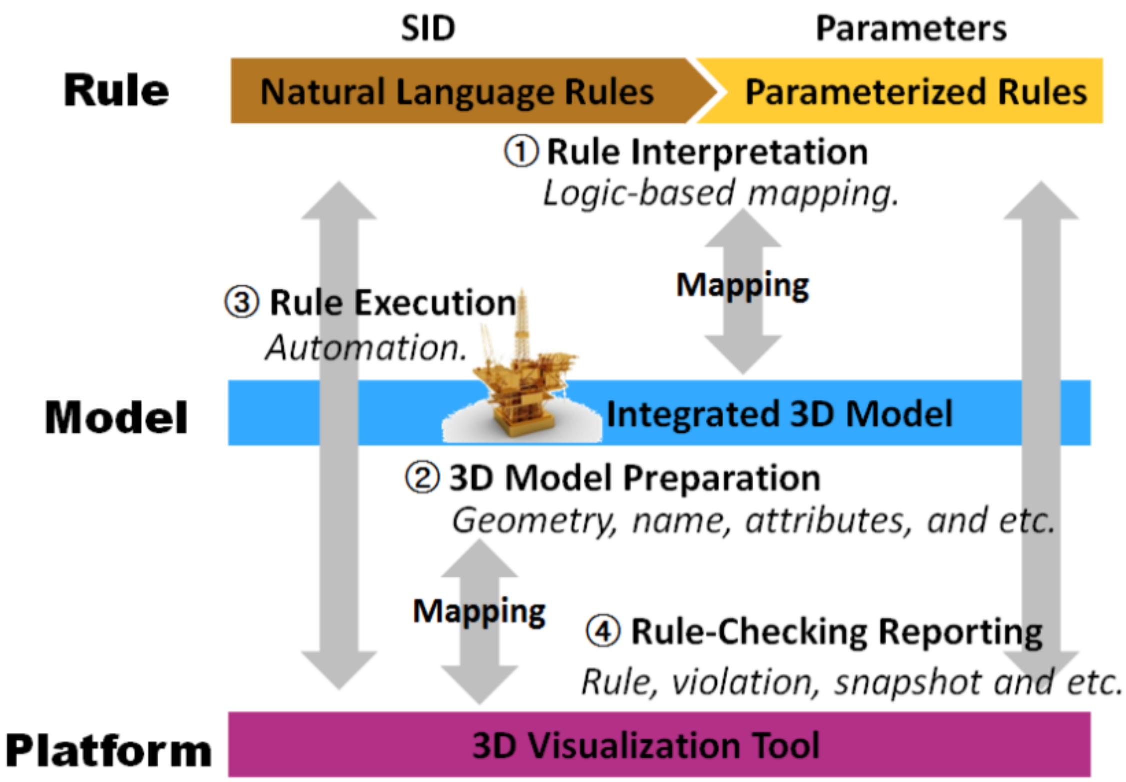


Fig. 2: Rule checking process for rule-based SID checking system.

4. IMPLEMENTATION AND CASE STUDY

The developed SID platform was implemented as a plug-in on an existing visualization platform (e.g., Navisworks). The interface includes three components next to a 3D model view (see Figure 3): (1) A box that allows checking of specific rule sets, (2) a box that displays the detected safety violation(s) according to the selection in (1), and (3) a box that provides a user with further information about the violation and an opportunity of leaving comments or personal remarks.

The developed approach was tested on a capital project model (e.g. off-shore oil platform) as shown in Figure 3. The rule-checking platform was tested for safe access/egress to work spaces on the platform. As recent and tragic events in the past have shown providing easy access/egress to work areas is important to maintain a safe and productive work environment. One research objective was to use the developed SID model review to find safety violations.

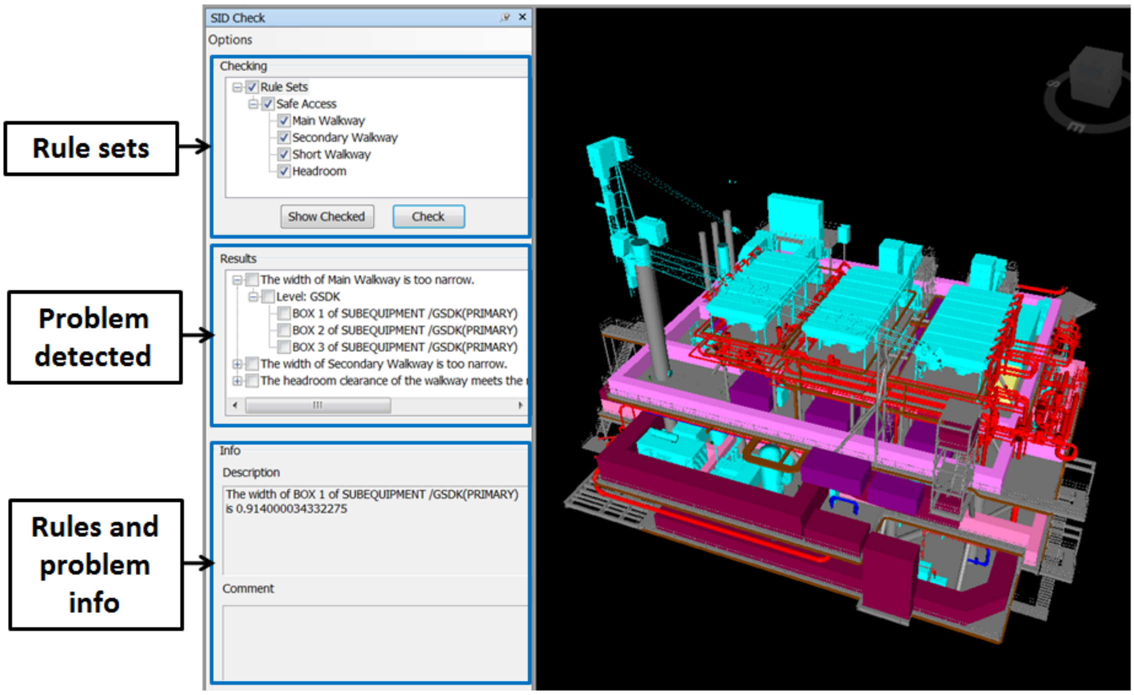
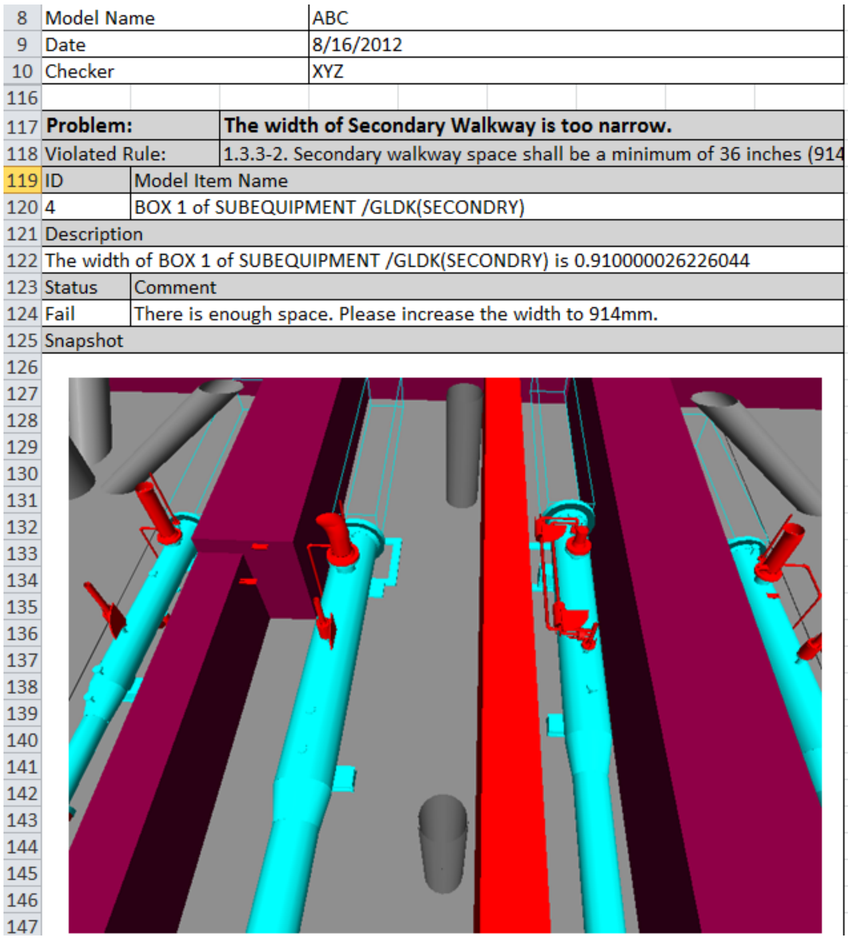


Fig. 3: Interface of developed plug-in on an existing 3D visualization tool.



8	Model Name	ABC
9	Date	8/16/2012
10	Checker	XYZ
116		
117	**Problem:**	**The width of Secondary Walkway is too narrow.**
118	Violated Rule:	1.3.3-2. Secondary walkway space shall be a minimum of 36 inches (914
119	ID	Model Item Name
120	4	BOX 1 of SUBEQUIPMENT /GLDK(SECONDRY)
121	Description	
122	The width of BOX 1 of SUBEQUIPMENT /GLDK(SECONDRY) is 0.910000026226044	
123	Status	Comment
124	Fail	There is enough space. Please increase the width to 914mm.
125	Snapshot	

Fig. 4: Example checking report in Excel format.

43 violations were detected by the automated SID rule-checker. They were categorized according by the level of severity. Figure 4 shows an example of the safety-rule checking report that was automatically generated. The associated objects in the model which cause a safety issue are highlighted in red. The developed interface also

displays an automated recommendation how the safety issue can be resolved. The recommendation is based on historic events and has embedded solutions there were pre-determined by humans to have previously successfully resolved the same or a similar issue. A user finally has control to approve the recommendation, implement the design chance, pass it back to the designer for a required change, and/or send it off for final approval by a SID engineer. It is important to keep the human involved in the final decision making process. The human user ultimately stays involved in an automated safety review process. A human may find more complex safety issues that the current automated SID rule-checking engine may not be able to solve. A human finally approves it and has a chance to score whether it was successful or not. This ensures that the automated safety rule-checking platform increases its success rate. Another advantage of the automatically generated and human-approved reports are that SID violations can be easily conveyed back to the designer and help them understand what the issue is even without visualizing the problem in 3D modeling software.

5. DISCUSSION AND CONCLUSIONS

As an application for the design-for-safety (DfS) concept, a preliminary automated SID rule-checking platform focusing on safety access/egress was developed. An application was developed based on an existing visualization platform and tested on a design for a capital facility project. The potential benefits of the application include: (1) add to the traditional safety design review process as a supportive tool that helps make SID engineers make better-informed and faster decisions, (2) instead of relying solely on the SID engineers' experience, the automated SID compliance checker provides consistency especially in large models reducing the human error of finding most but not all safety issues, (3) allowing SID engineers to concentrate and spend time on safety issues that are too complex for an automated SID checker to find, and (4) the developed tool allows designers to identify and reduce potential design errors/unsafe design early in the design phase and even before it is handed off to SID engineers thus ensuring DfS concepts by empowering many project stakeholders as early as possible in the design and review process of projects. Future research will need to (1) to explore the requirements and feasibility of implementing many other SID rules based on the proposed methodology, and (2) to study the effectiveness of such system as an assistive system for designers and SID engineers in practice. As such, the reliability of any rule checking system largely depends on the correctness of the 3D model, e.g. object properties and naming (Eastman et al. 2009).

6. REFERENCES

Bello, M. A. (2012). Minimizing Impediments to Design for Construction Safety (DFCS) Implementation on Capital Projects, Doctoral Thesis, Carnegie Mellon University, 91.

Chevron Corporation (2012). Chevron Safety in Designs Manual (SID).Eastman, C., Lee, J. M., Jeong, Y. S., & Lee, J. K. (2009). Automatic rule-based checking of building designs. *Automation in Constructio*n, Elsevier, 18(8), 1011-1033.

Federal Aviation Administration (2005, Aug. 10). Human Factors Policy FAA Order 9550.8A. Retrieved 1 Feb. 2013 from http://www.hf.faa.gov/docs/508/docs/HForder.pdf.

Frijters, A. C., and Swuste, P. H. (2008). Safety assessment in design and preparation phase. *Safety Science*, Elsevier, 46(2), 272-281.

Gambatese, J., and Hinze, J. (1999). Addressing construction worker safety in the design phase: Designing for construction worker safety. *Automation in Construction*, Elsevier, 8(6), 643-649.

Lee, J. K., Eastman, C., Lee, J., Kannala, M., and Jeong, Y. S. (2010). Computing Walking Distances within Buildings based on the Universal Circulation Network. *Environment and Planning B: Planning and Design,* 37(4), 628-645.

Qi, J., Issa, R.R.A., Hinze, J., Olbina, S. (2011), Integration of safety in design through the use of building information modeling, *Proceedings of the 2011 ASCE International Workshop on Computing in Civil Engineering*, pp. 698–705.

Toole, T. and Gambatese, J. (2008): The Trajectories of Prevention through Design in Construction: *Journal of Safety Research*, 39 (2), 225-230.

Victoria, W. (2005). Designing safer buildings and Structures. A Guide to Section 28 of the Occupational Health and Safety Act.

Zhang, S., Teizer, J., Lee, J. K., Eastman, C. M. and Venugopal, M. (2013). Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in Construction*, Elsevier, 29, 183–195.

Jones A. S. (1994a). The future of electronic publishing, *Journal of modern communications*, Vol. 3, No. 5, 213-232.

Smith A. S. and Jones A. B. (1994). Published electronically, *Proceedings of 4th international conference of office systems* (Jones A. B., editor), University of New Brunswick, 213-232.

A BIM ASSISTED RULE BASED APPROACH FOR CHECKING OF GREEN BUILDING DESIGN

Yi-Wen Chen & Shang-Hsien Hsieh
Department of Civil Engineering, National Taiwan University, Taipei, Taiwan

ABSTRACT: *Since the publication of green building standards from the last decade, the designer of green buildings have often encountered the challenges of limited time but considerable complexity in the process of evaluating their design according to the rules specified in the standards. Also, the design process is usually an iterative one, which includes rule-checking tasks that are tedious and repetitive. With the advancement of technologies in Building Information Modeling (BIM), artificial intelligence, and Virtual Reality (VR), this research investigates and develops a BIM-assisted Rule-based approach for automating checking of green building design. The developed approach utilizes as much information available in a building's BIM model as possible to automate the design evaluation complied with green building standards. It also provides visual feedbacks through the BIM model to assist the designer in green building design. To evaluate and demonstrate this approach, an Application Programming Interface (API) tool has been developed in this research to extend the capability of BIM software for both automatic rule-checking of green building design and real-time visualization of feedbacks from the rule-checking. A rule base is used to manage the design rules specified in green building standards and facilitate the automation of rule checking. In addition, visualization of the rule-checking results (e.g. highlights of places in the design that do not satisfy the design requirements) is supported in a 3D VR environment of a building's BIM model.*

KEYWORDS: *Building Information Modeling, BIM, Rule Checking, Green Building Standards, Rule-based System, Application Programming Interface, Visualization.*

1. INTRODUCTION

To address the global warming crisis, many countries have started to incorporate their building designs with sustainable elements and developed their green building standards over the past decade. However, due to their differences in climate and natural environmental conditions, the standards developed may place focus on different environmental issues. Table 1 shows the top two categories in different green building standards. For example, the Green Mark of Singapore's Building and Construction Authority (BCA) focuses on Energy Efficient and Environmental Protection, which helps reduce both the potential impact on the environmental and energy consumption (Building and Construction Authority, 2013a, 2013b); while Leadership in Energy and Environmental Design (LEED) and Building Research Establishment's Environmental Assessment Method (BREEAM) mainly focus on Energy and Indoor Environmental Quality (Green Building Council, 2002; BRE Global Ltd, 2012). In Taiwan, to reduce the heat island effect and the carbon dioxide emission in the subtropical climate environment, the Green Building Evaluation Manual (EEWH), that is based on the Green Building Code in Taiwan, focuses on Energy Conservation and Ecology (Liu and Chen, 2011).

Table 1: Comparison of top two weighting subjects in green building standards

	LEED	BREEAM	BCA Green Mark	EEWH
Top two subjects	Energy & Atmosphere	Energy	Energy Efficient	Energy Conservation
	Indoor Environmental Quality	Health & Wellbeing	Environmental Protection	Ecology

To achieve green building design, the designer often needs to spend considerable effort and amount of time in the tedious process of evaluating their design against the rules specified in the standards. Usually the design process is an iterative one and therefore the rule-checking tasks for complying with the requirements specified in the

Citation: Chen, Y-. W. & Hsieh, S-. H. (2013). A BIM assisted rule based approach for checking of green building design. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

standards need to be carried out repeatedly for many times. In a building project that is complex but has only limited design time, the quality of the green building design may be affected by the limited design iterations the designer can afford to have (Motawa and Carter, 2013). Therefore, with the advancement of computer technology and the emerging BIM (Building Information Modeling) technology (Eastman et al., 2011) for better building information modeling and management, some researchers (e.g. Wu and Chang, 2013; Sanguinetti et al., 2009; Chen et al., 2012) have developed systems or tools that are able to automatically calculate the energy conservation values to reduce manual calculation time and errors during the design process. In these systems, the calculation rules are implemented in the software program and cannot be easily modified or extended without recompilation of the program when the rules in the standards may be updated. Other researchers (e.g. Ding et al., 2006; Lee et al., 2010) have developed rule-based systems for checking the accessibility and fire safety rules in the design codes, showing the potential of applying rule-based systems to green building design. Moreover, a rule-based design checking system allows the designers to check their building design against different criteria in rules (Eastman et al., 2009).

The objective of this paper is to take advantage of and integrate BIM, rule-based reasoning, and Virtual Reality (VR) technologies for helping the designers in automatic checking of green building design with real-time visualization of feedbacks from the rule-checking. To evaluate and demonstrate the approach, a prototype rule-based system for automatic checking of green building design, called Green Building Design Assistant (GBDA), has been developed to provide the designers with functionalities that show the differences between the current design results and the requirements in the standards. The current scope of the rule-checking implementation is on the ecology part of the Taiwan's green building design code, which uses the equivalent carbon dioxide amount reduced by plant greening as an index for evaluating the design of plant greening at the building site.

2. BIM TECHNOLOGY AND RULE-BASED APPROACH

BIM technology (Eastman et al., 2011) is the process of creating and managing parametric 3D digital models of a structure (or facility) during the structure's life cycle. It is an emerging technology that has the potential to revolutionize the business in the architecture, engineering, and construction (AEC) industry. The current design approach that is mainly based on the 2D CAD drawings will be replaced by the 3D BIM approach in the foreseeable future. Because a 3D BIM model of a building contains not only the geometric information of its components that correspond to physical building components in the real world, but also the attribute information (e.g. materials, color, etc.) of the components and the relationships among the components, it provides much information useful for automatic calculation and rule-checking in green building design. Also, it provides a very good platform for visualization of the calculation and rule-checking results.

A rule-based system (Hayes-Roth, 1985) is a system that can store knowledge or experiences in terms of rules and use them for making effective judgment in the real world situations. Generally speaking, the system consists of three main parts: working memory, inference engine, and knowledge base (rules), as shown in Fig. 1. The working memory passes facts to the inference engine to initiate the process of reasoning with the rules stored in the knowledge base. The result of the reasoning is then passed back to the working memory and may be displayed in the user interface. The rules in the knowledge base can be easily maintained (editing, adding, and deleting) without modifying any system software. This feature and its rule-based reasoning capability make it very suitable for managing design rules in codes or standards and performing design code checking for the designer.

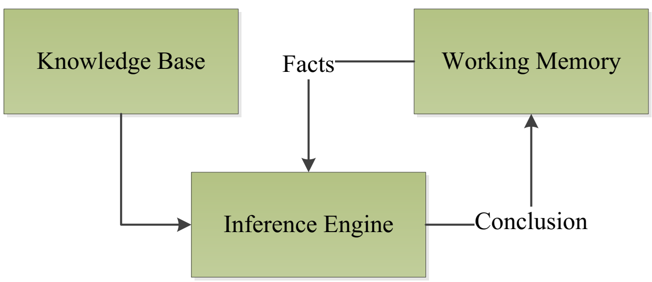


Fig. 1: Basic components of a rule-based system

3. THE PROTOTYPE DESIGN CHECKING SYSTEM: GBDA

The prototype rule-based system for automatic checking of green building design, named Green Building Design Assistant (GBDA), has been developed in this work using the Application Programming Interface (API) of Autodesk's Revit and the Neo4j NOSQL graph database. As shown in Fig. 2, GBDA includes three major components: Revit user interface, calculation and model control system, and rule engine system. The Revit user interface is written in .NET C# Windows Form, and allows designers to input the basic information of a building, as illustrated in the (a) part of Fig. 3. Another feature of the Revit user interface is the provision of the evaluation results, as shown in the (b) and (c) parts of Fig. 3. The calculation system contains all the evaluation formulas, which extracts the required information from a BIM model and calculates the value demanded by design codes. The model control system, on the other hand, is for retrieving the evaluation results from the rule engine and displaying the results in a BIM model with highlighted elements or auxiliary lines. Basically, the rule engine uses the calculation results (Facts) in the calculation system to perform automatic rule evaluation, and then sends the evaluation results to the model control system. The rule engine serves as the connection between the Revit API and the Neo4j database, and helps GBDA to perform real-time rule evaluations.

3.1 Calculation and model control system

The calculation and model control system shown in Fig. 4 consists of two parts: the calculation system and the model control system.

The calculation system implements the formulas in the Green Building Code with the help of the model extractor to extract needed data from the BIM model. In order to reduce the model preparation work in manually entering properties for rule evaluation, the calculation system uses categories and properties to identify the requiring data in a BIM model. Take tree-counting as an example, when a designer enables the rule evaluation function, GBDA starts comparing the names labeled in the tree elements of the BIM model to the names of the tree list stored in the database for tree identification as shown in Fig. 5(a). Also, the attributes of the tree objects, as shown in Fig. 5(b), are used to flag if the tree is an "original" one or not. This approach enables GBDA to reduce the complexity and time invested on manual rule evaluation and makes the rule evaluation more accurate and efficient.

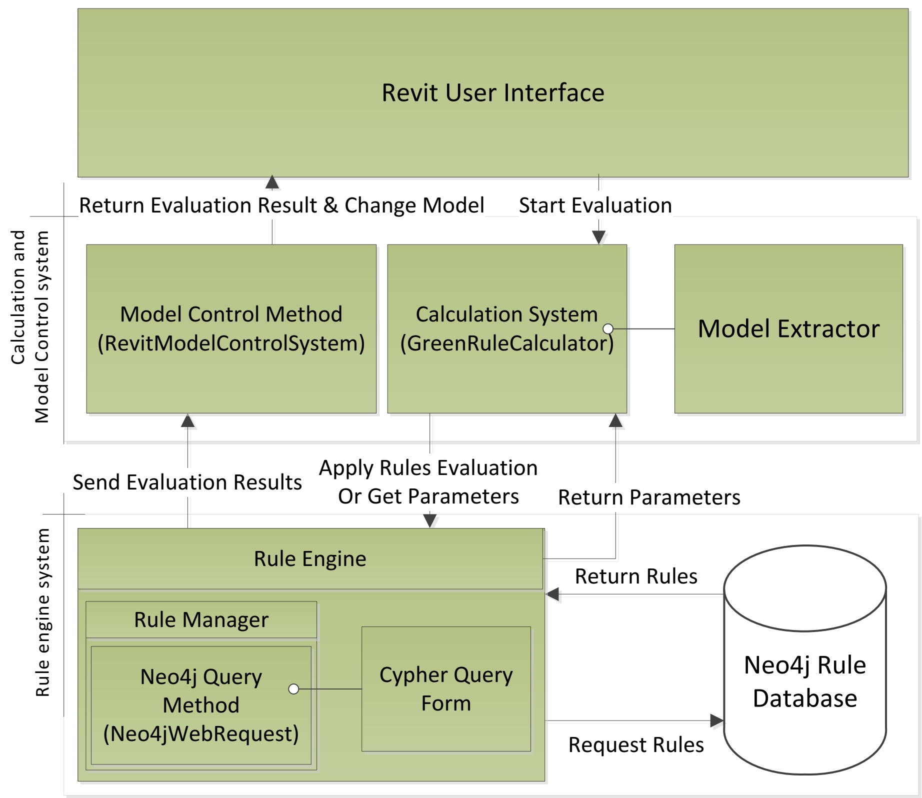


Fig. 2: System architecture of GBDA

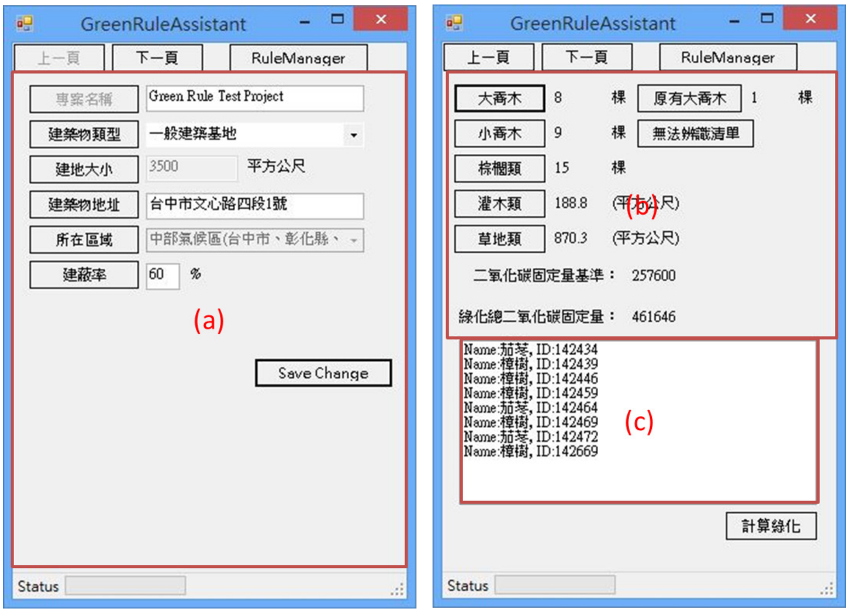


Fig. 3: GBDA's Revit User Interface: (a) building information, (b) evaluation result, and (c) object list display

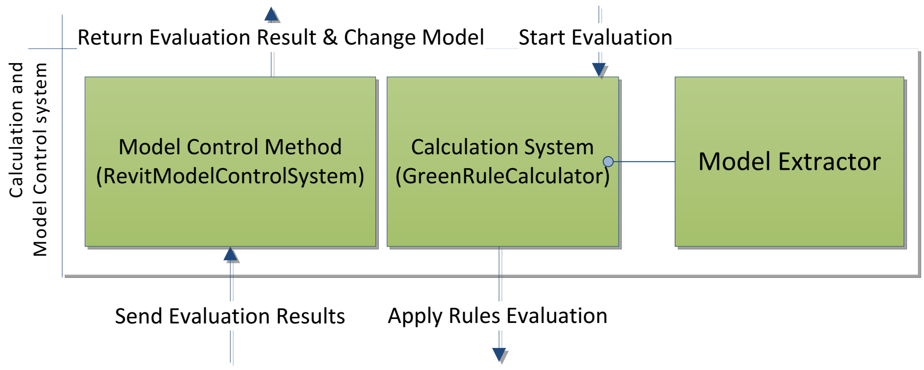


Fig. 4: Calculation and Model Control System

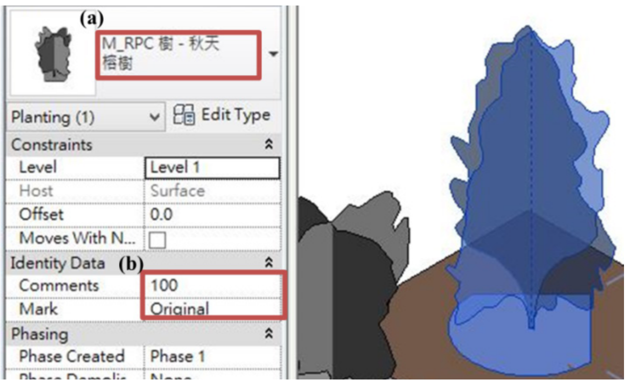
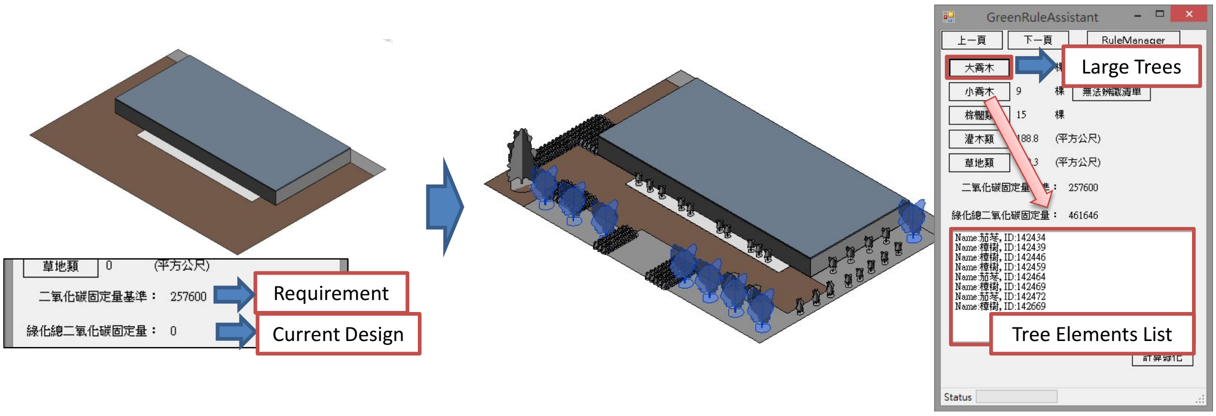


Fig. 5: (a) Category and name of the tree, (b) Labels embedded in the attributes

Through the model control system, the evaluation result can be illustrated in both the BIM model and data tables for assisting sustainable building design. Let us continue to use the example of greening with trees. The GBDA user interfaces provide both the detailed information about each type of trees (including total numbers, names with ID numbers, locations in the BIM model, etc.), as shown on the right side of Fig. 6, and the calculated result of the code requirement and the evaluated value for the current design, as shown on the left bottom side of Fig. 6. Furthermore, the user interface can interact with the BIM model in Revit to generate real-time visualization for the trees listed in the object list display area. When the designer clicks on either the tree type buttons or the trees on the list, the tree objects (or elements) in the model get highlighted. In this way, not only can the designer know the current design value, but also have a good idea about the contributions among different greening strategies depicted in the BIM model.



(a) Real-time evaluation (b) Selection by tree type and interaction with Model

Fig. 6: Feedback visualization of interactive design evaluation

3.2 Rule engine system

Fig. 7 shows the implementation of the rule-based system (as previously shown in Fig. 1) in GBDA. The calculated results are sent as facts from the calculation system and the evaluation with rules contained in Neo4j rule database is conducted in the rule engine system. Then, the evaluation result is sent as a conclusion to the model control system for visualization.

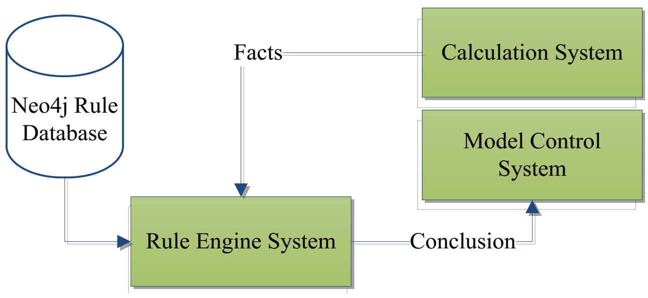


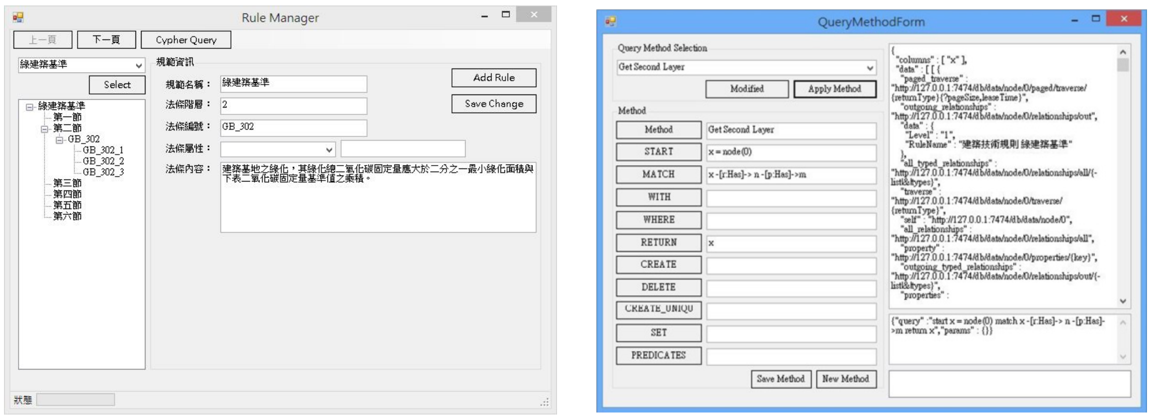
Fig. 7: Rule Engine System data flow

3.2.1 Rule engine control interfaces

To facilitate the management of rules, an interface called Rule Manger is designed for GBDA. The Rule Manger, as shown in Fig. 8(a) displays the tree structure of all rules in the rule base on the left side and the attributes of the selected rule on the right side. It also provides functions for adding new rules and modifying the properties of existing rules. Moreover, a Query Method Form is implemented (see Fig. 8(b)) to provide a user interface for defining the query methods that the rule engine can follow the defined paths to get access to the rules created by the users (usually the rule managers) in the rule database. As shown in Fig. 8(b), the query methods are stored in the XML format.

3.2.2 Rule interpretation

The rules in a green building code are usually expressed in natural language and tables. To convert the rules into a database, we need to extract the conditions and properties from the rules and distinguish all properties contained in the rules. Let us take the rule No. 302 in Taiwan's Green Building Code as an example Fig. 9 shows that the interpreted rule includes basic information such as "RuleName" representing the rule number and properties. Properties with different requirements will be stored in different sub-nodes of the node GB_302 and relationships between the node β and the sub-nodes are represented as conditions. This approach allows us to



(a)Rule Manager (b) Query Method Form

Fig. 8: Rule engine control interfaces

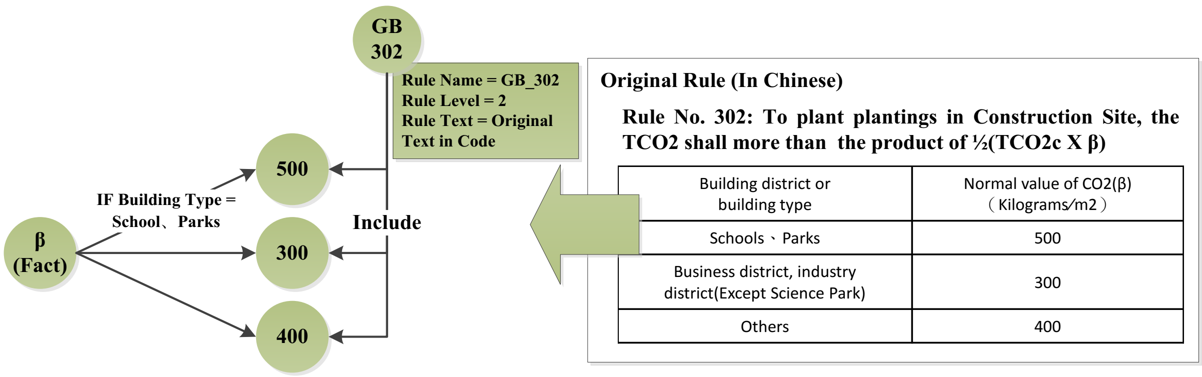


Fig. 9: Translating natural language rules into a database

translate the natural langrage rules into a NOSQL database object, which is used later for automatic rule evaluation

3.2.3 NOSQL rule database

For the flexibility in the rule management and rule base extensibility, rules in GBDA are stored in a NOSQL database. With this type of database, three major parts of a rule-engine: facts, conditions and actions, are represented by nodes of facts, relationships between nodes, and the directions of relationships, respectively, as illustrated in Fig. 10. By using the nodes to represent facts, the system can easily store non-structured data and extend the properties of nodes when there is a need to modify current rules or implement new ones. Using relationships to connect nodes for forming paths with different conditions allows for flexible formulation of rules. The direction of a relationship represents the action of reasoning and the process of a complete path of the nodes represents the evaluation of a corresponding rule in the rule base.

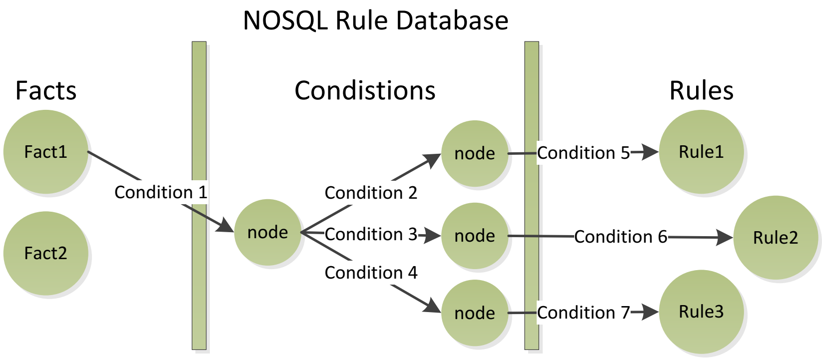
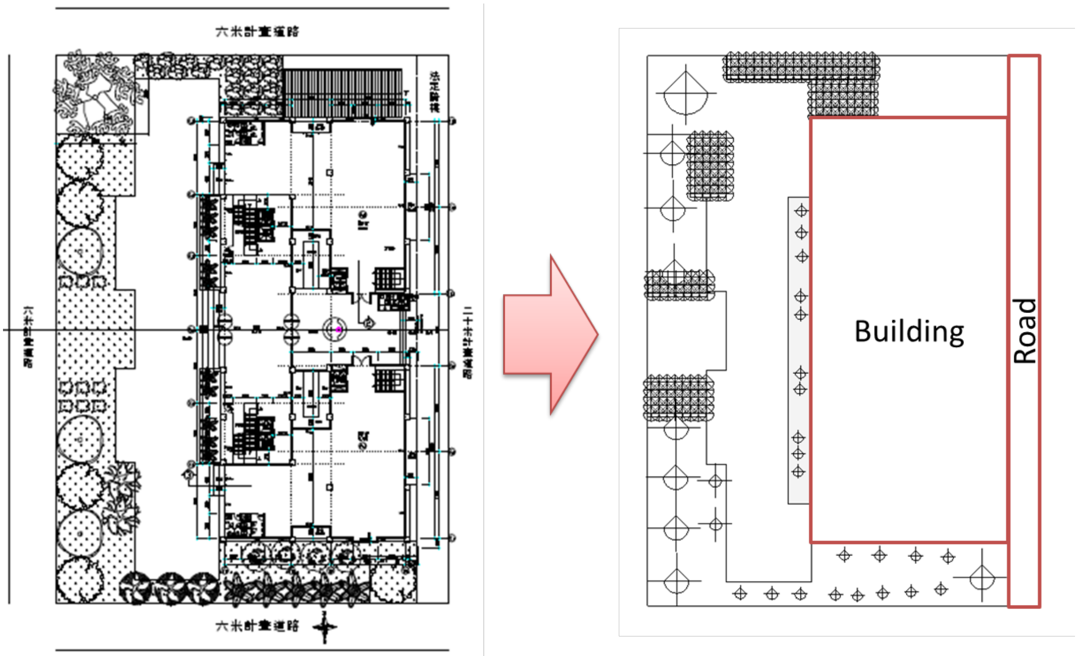


Fig. 10: NOSQL rule base structure

4. A CASE STUDY

In order to demonstrate and verify the proposed approach, this research uses a sample project documented in Taiwan's Green Building Code as a case study. The design plan in the Code is used to establish a BIM model of the same layout and the same tree types as shown in Fig. 11, and then the GBDA rule evaluation is applied to this model. Finally the results calculated by GBDA are compared with those provided in the sample project.



(a) Sample case in the Code (b) Plan view of the corresponding BIM model

Fig. 11: Sample project documented in Taiwan's Green Building Code

Because GBDA counts every trees in the BIM model and identifies tree type based on the tree database built in the system and the attributes of the tree objects in the model, its calculation on the number of each type of trees matches accurately with the result of the sample in the Code. Moreover, with GBDA, the designer can easily adjust the plant greening design, quickly obtain all the needed calculation associated with the adjusted design, and clearly visualize the adjusted design in the 3D BIM model as well as the numerical results in text-based user interfaces. For example, Fig. 12 shows a modified green design on the sample project and the corresponding updated results of rule evaluation.

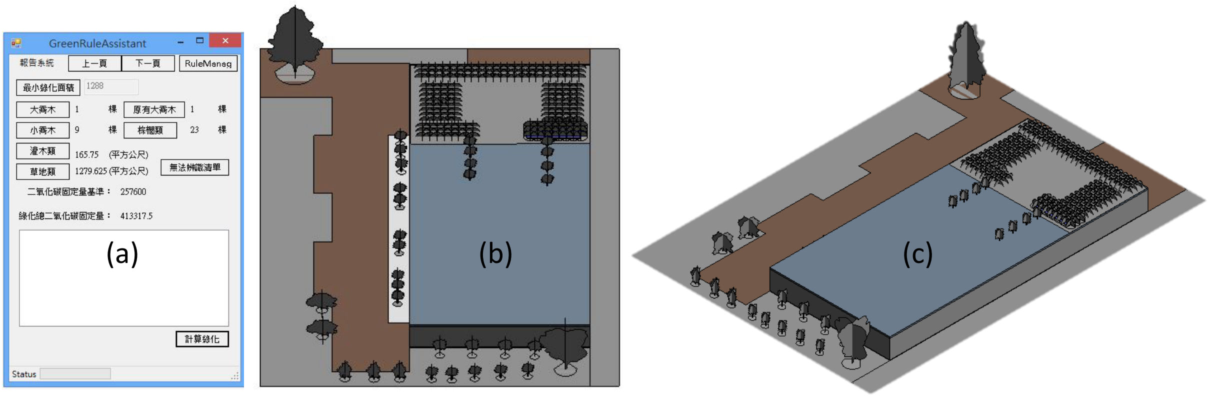


Fig. 12: Rule evaluation during design iteration: (a) Evaluation result, (b) BIM model top side view and (c) BIM model 3D view

5. CONCLUSIONS

A BIM-assisted Rule-based approach for automating checking of green building design has been presented in this paper. A prototype system that integrates BIM tool, NOSQL rule base, and rule-based engine has been successfully developed and tested to show the feasibility of the proposed approach. The automatic calculation and rule-checking features relieve the designer from the tedious, repetitive and error-prone manual operations in the iterative process of green building design. The application of 3D BIM model for real-time visualization of feedbacks from the rule-checking greatly facilitates the designer's decision-making and communications with his or her clients.

6. ACKNOWLEDGEMENT

The authors would like to thank the Technology Development Program for Academic, Ministry of Economic Affairs, Taiwan (Project No. 101-EC-17-A-15-S1-223) for its partial financial support. Also, the helpful discussions on Taiwan's architecture design practice and issues related to green building design with Mr. Borden Tseng, Mr. Tunghan Wu, and Mr. Zizi Huang of Q-LAB, Taipei, Taiwan are greatly appreciated.

7. REFERENCES

Lin H. T., Chuang H. W., Chang C. Y. & Chen C. N. (2012). Green Building Evaluation Manual – Basic Version (EEWH-BC). Architecture and Building Research Institute, Ministry of the Interior, Taiwan, 163 pages (in Chinese).

Building and Construction Authority (2013a). BCA Green Mark [Online], Available: http://www.greenmark.sg/index.html.

Building and Construction Authority (2013b). BCA Green Mark for New Residential Buildings, Singapore.

Green Building Council (2002). Green Building Rating System for New Construction & Major Renovations (LEED-NC), Version 2.1, U.S.A., 67 pages.

BRE Global Ltd. (2012). BREEAM Refurbishment. Domestic Buildings Technical Manual, SD5072-2012-1.0.2, United Kingdom, 325 pages.

Chen P.-H., Chuang P.-C. & Kan M.-S. (2012). Study on Integration of Building Information Modeling (BIM) and Taiwan's Green Building Standard - Taking Building Envelope for Example. Proceeding of the Twenty-fifth KKCNN Symposium on Civil Engineering, October 22-24, 2012, Busan, Korea.

Ding L., Drogemuller R., Rosenman M., Marchant D. & Gero J. (2006). Automating Code Checking for Building Designs - Design Check. In: Brown K., Hampson K. & Brandon P. (eds.) Clients Driving Construction Innovation: Moving Ideas into Practice, Brisbane, Australia: CRC for Construction Innovation, 113-126.

Eastman C., Lee J. M., Jeong Y. S. & Lee J. K. (2009). Automatic Rule-based Checking of Building Designs. Automation in Construction, 18, 1011-1033.

Eastman C., Teicholz P., Sacks R. & Liston K. (2011). BIM Handbook : A Guide to Building Information Modeling for Ownwes, Managers, Architects, Engineers, Contractors, and Fabricators, John Wiley and Sons, Inc.

Hayes-Roth F. (1985), Rule-based systems, Communications of the ACM, 28(9), 921-932, New York, NY, USA: Assoclation for Computing Machinery.

Lee J.-k., Eastman C. M., Lee J., Kannalaô M. & Jeong Y.-S. (2010). Computing Walking Distances within Buildings Using the Universal Circulation Network, Planning and Design, 37(4), 628-645.

Liu T. F. & Chen C. N. (2011). Comparison of Green Building Rating System between Taiwan and other Countries. Sinitech Engineering Journal, 113, 87-94. (in Chinese).

Motawa I. & Carter K. (2013). Sustainable BIM-based Evaluation of Buildings, Procedia - Social and Behavioral Sciences, 74, 116-125.

Sanguinetti P., Eastman C. & Augenbroe G. (2009). Courthouse Energy Evaluation: BIM and Simulation Model Interopreability in Concept Design, Proceeding of Building Simulation, July 27-30, 2009, Glasgow, Scotland. 1922-1929.

Wu I. C. & Chang S. (2013). Visual Req Calculation Tool for Green Building Evaluation in Taiwan, Automation in Construction, http://dx.doi.org/10.1016/j.autcon.2013.01.006.

DESIGN-FOR-SAFETY ANALYSIS SUPPORT SYSTEM FOR BUILDING DESIGNERS

Imriyas Kamardeen
Faculty of Built Environment, University of New South Wales, Australia

ABSTRACT: *Accident prevention and control in construction is a continuing challenge. The construction industry has one of the worst workplace health and safety records globally. There is considerable evidence that decisions made by designers early in the development process have significant implications for the safety of workers on construction sites. Recognizing the important contributions which good design can make in improving safety performance, many governments around the world have mandated Design-for-Safety (DfS) in their workplace health and safety legislations. Designers in many countries are now required by law to include DfS in their design practices, which is a major modification to their traditional roles and responsibilities. Nonetheless, research shows that most designers lack the expertise required for effective implementation of DfS. This paper discusses the development of a mobile computing enabled knowledge management system that can assist designers to reduce accidents in the construction industry through safe designs. The system can provide modular and just-in-time knowledge support to designers during the design process. The utilization of the system could foster enhanced DfS implementation in industry and thereby accident reduction in construction projects.*

KEYWORDS: *Workplace health and safety, Design for Safety, Knowledge Management System, Mobile Computing*

1. INTRODUCTION

Accident prevention and control in construction is a continuing challenge. Despite many initiatives to improve safety, construction has one of the worst industrial safety records of all sectors, including high-risk industries such as chemical, mining, electrical and transportation (Hu et al. 2011). In Australia, the construction industry's accident rate of 22 per 1000 workers is much higher than the national rate for all industries of 14 per 1000 workers. Its fatality rate of 5.9 per 100 000 workers is almost three times the rate for all industries, which is 1.9 per 100 000 workers (Safe Work Australia 2011). This abysmal record is reflected elsewhere. In the US, for example, the construction industry accounts for 19% of all workplace fatalities and remains the highest source of fatal workplace accidents (Bureau of Labor Statistics 2010). In the UK, the construction fatality rate constitutes 21.5% of total workplace fatalities (Health and Safety Executive 2010) while reportable non-fatal injuries averaged 16 per 1000 workers, significantly higher than the overall average of 10 per 1000 workers (Labor Force Survey 2009).

Traditionally, safety has been the responsibility of builders who develop detailed safety management plans and implement them on site to reduce accidents. However, there is considerable evidence that decisions made by designers early in the development process have significant implications for the safety of workers on construction sites. Behm's (2005) research of 224 fatalities showed that 42 per cent of which were avoidable if design for construction safety concept had been applied. A report on design-related work injuries in Australia found that design-related issues contributed to 37 per cent of workplace fatalities and at least 30 per cent of injuries (Creaser 2008). Similarly, a detailed review of 100 construction accidents in the UK found that in almost half of all cases (47%) a design change would have significantly reduced the risk of injury (Gibb et al. 2004). Hence, designers have a role in reducing accidents in construction too. The concept of Design-for-Safety (DfS) has emerged from this argument and is a methodology applied by designers through the different phases of the design process to identify and mitigate safety hazards caused by design decisions.

Recognizing the important contributions which good design can make in improving safety performance, many governments around the world have been promoting DfS vigorously via a variety of mechanisms. Some governments have in fact mandated the use of DfS in their workplace health and safety legislations. Designers in many countries are now required by law to include DfS in their design practices, which is a major modification to their traditional roles and responsibilities. Nonetheless, industry surveys show that most designers lack the expertise required for effective implementation of DfS because their design degrees did not cover onsite OHS aspects adequately.

Citation: Kamardeen, I. (2013). Design-for-safety analysis support system for building designers. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Several resources claiming to support designers with DfS analysis are already available. Nonetheless, the industry is still faced with challenges for their effective implementation. Spiteri & Borg (2006) argued that designers constantly require *modular* and *just-in-time* knowledge support during the design process. *Just-in-time* implies that knowledge is provided immediately when it is required to ensure that correct decisions are taken at differing design stages. This knowledge has to be presented in a *modular* format, making it possible to structure the information required into components that can be translated into usable chunks, which can then be *reused elsewhere* in similar design situations. They further suggested that mobile knowledge management systems are ideal tools for providing the right knowledge within the right context at the right time to architects. Hence, the aim of this research was to develop a mobile computing enabled knowledge management system that can assist designers to reduce accidents in the construction industry through safe designs.

2. THE CONCEPT OF DESIGN-FOR-SAFETY (DfS)

In order to better manage and improve worker safety, there is a wealth of research to identify and understand factors contributing to workplace injuries. Traditionally, the design-bid-build model of proceeding construction activities led to the perception that ensuring the safety of construction workers is largely left to construction contractors (Hinze and Wiegand 1992; Rechnitzer 2001). However, in recent years especially the last two decades, taking safety into consideration well ahead of the start of the construction work has gained momentum. A frequently cited research by Szymberski (1997) illustrated the relationship between project schedule and the ability to influence safety, as shown in Fig. 1. This seminal work puts forward the concept that risks associated with a project are mostly determined at the conceptual stage of the project, whereas when the project reaches the actual construction stage little can be done to improve safety. Since then, attention has been paid to quantify the relationship between design and construction accidents.

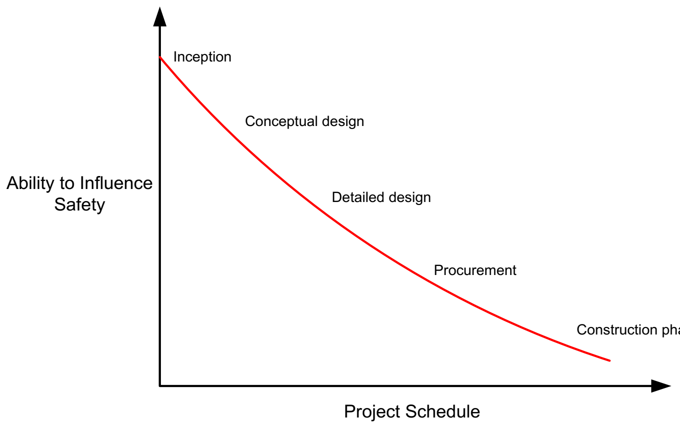


Fig. 1: Time vs Safety influence curve (Source: Szymberski 1997)

From the above discussion it can be seen that taking account of safety in the design stage is of vital importance in construction and hence the concept of DfS or design for construction safety has been formally proposed in research. According to Gambatese *et al.* (2005), "designing for construction safety entails addressing the safety of construction workers in the design of permanent features of a project". This means that DfS is a proactive prevention of potential hazards, in other words, it is directed at eliminating potential hazards at source before they outset; i.e., dealing with problems in the project design stage more than in the project implementation stage (Fadier and De la Garza 2006).

Concerning the benefits of DfS, the most notable and direct benefit is reduced hazards and thereby less accidents on construction sites. Moreover, three added benefits of DfS can be summarized as follows (Toole and Gambatese 2008):

- the proactive identification and avoidance of hazards in the design stage is considered safer and more cost effective than reactive management of risks in the construction stage;
- design professionals are more knowledgeable of technical issues, such as stresses and electricity in construction project. Therefore, the DfS concept of requiring this group to consider safety in their work can achieve better use of human resource; and

- DfS helps to raise awareness of safety in construction by including all entities, especially designers, in the effort to reduce construction injuries. This, obviously, has important implications for construction practices.

3. THE PROCESS OF DfS

DfS is an iterative process that is applied in different phases of design development, and involves a multidisciplinary team. Fig. 2 illustrates the various phases in the design process and how DfS is integrated into these phases. It also shows the stages involved in the DfS process.

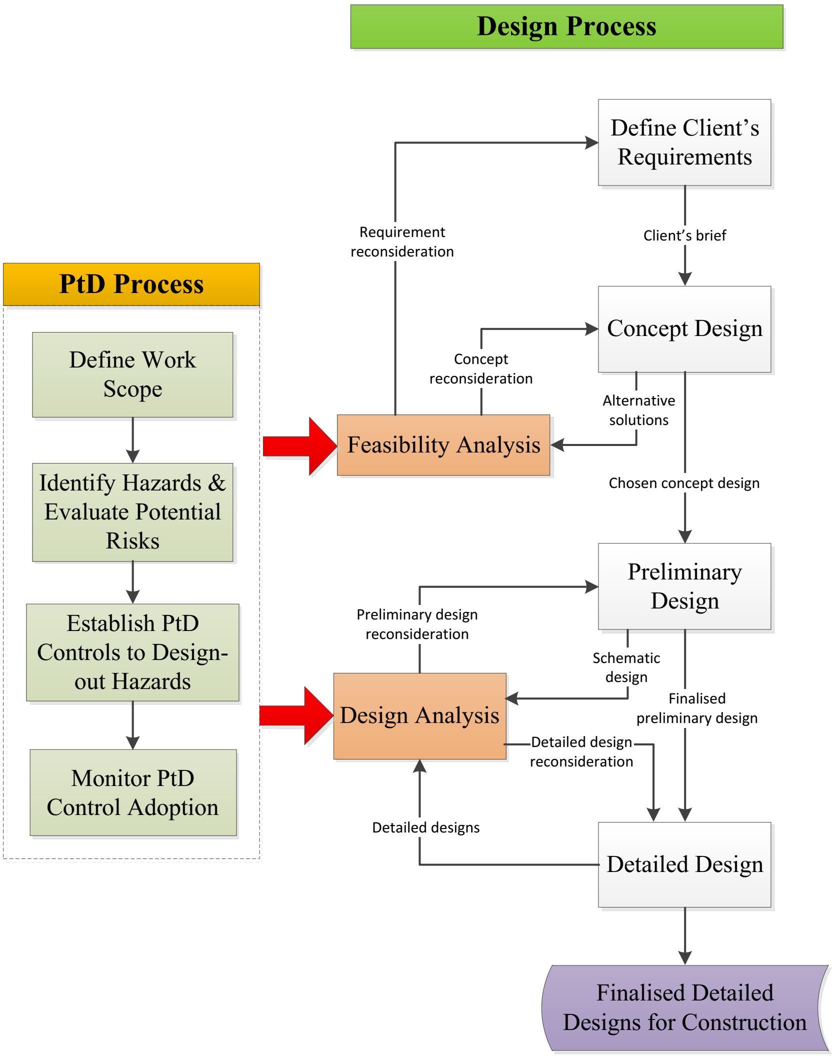


Fig. 2: DfS process

The design process begins by defining client's requirements. In this phase, the design team works closely with the client to determine the requirements for the project in terms of its functionality, performance level, design and aesthetic features and other characteristics such as sustainability, budget and time constraints. The outcome of this phase is a client's brief, which serves as a foundation for the remaining phases of the design process.

In the concept design phase, alternative project solutions to meet the client's requirements are identified. Following that, feasibility assessments of the concept proposals are accomplished with the aim of selecting the optimum project solution that is achievable, both technically and financially. Concept design DfS forms part of feasibility assessments. The objective of concept design DfS is to evaluate concept design proposals from a workers' health and safety perspective and to establish a safe design basis for a chosen concept design to carry on into the preliminary design phase. In this analysis, considerations need to be given to both the project site context and concept design alternatives. By establishing the relevance of the project context, advance thinking about possible hazards and safety implications to be provided and visibility to DfS considerations to be given from the outset. Consequently, concept level DfS suggestions are drawn for a preferred concept design, including: construction methods and techniques, orientation of the facility, use of prefabrication, types of temporary structures, types of materials and equipment, etc.

The chosen concept design is further defined in the preliminary design phase. An overall project configuration is defined whereby system and component level design requirements are established. Furthermore, schematic drawings, layout definition drawings and other engineering documentations are developed to provide an early project configuration control. DfS efforts in the preliminary design phase are an incremental of the concept design DfS. First, an audit on the preliminary design is to be undertaken to ensure that concept design DfS suggestions have been absorbed in reasonably. Then, a hazard analysis will proceed from a facility level analysis to system and component level analysis. The study of project scope and sketch designs will identify and analyze work trades to be involved in the project. For example, deep excavation, works at heights, manual handling, management of hazardous materials such as asbestos and waste, temporary works, erecting structures, crane use, works over water, confined space works, etc. Having identified the work trades and qualitatively analyzed potential hazards in the project, high level DfS suggestions will be made for risk control through preliminary design revision.

The detailed design phase produces different types of design drawings and specifications for components and systems (architectural, structural, MEP and Fire system, etc.), thoroughly describing their interfaces and functions so that they can be built on site. Detailed design DfS efforts analyse the designs and specifications of individual elements to locate hazards caused by design decisions. The risk analysis step will then determine which of the hazards are removable by design revisions and which are to be managed on site. Subsequently, DfS suggestion reports will be produced for design revisions. The risk monitor step will oversee how the DfS suggestions are embraced in revising the original designs.

4. REVIEW OF EXISTING RESOURCES FOR DfS

In order to implement DfS, designers must thoroughly know the construction contexts of their designs. Every design creates a construction context, which dictates the level of hazard posed by the design choice. The construction context can be usefully conceived of as including five elements: site settings – site terrain condition, space and accessibility, road and traffic condition and vicinity; task settings – location of the task and temporary structures/facilities needed to build it; materials – type and nature of materials used; equipment – type and nature of equipment used; and labor - type and skill level. A construction accident can emanate from one or a combination of the contextual elements. DfS must therefore perform a what-if analysis for all possible design options for a building project to take account of their construction contexts and make safe design choices, using an iterative process from inception through the detailed design phases. The critical challenge here is the skill gap of designers. Since designers are predominantly trained in design principles and they do not often work on construction sites, they usually have only limited practical knowledge of construction operations and contexts triggered by their designs. Detailed knowledge of construction technology, OHS and risk management is essential to undertake meaningful DfS analyses.

Several DfS resources claiming to support designers in DfS analyses are already available. These resources fall into two categories: frameworks that elaborate on DfS procedures; and tools that help to identify specific risks that can be addressed in the DfS process. Under the category of DfS frameworks: in Australia, Australian Safety and Compensation Council published Guidance on the Principles of Safe Design for Work while the WorkCover introduced the Construction Hazard Assessment Implication Review (CHAIR) (Mroszczyk 2008). The UK Health and Safety Executive (2010) also developed several documents to assist designers with DfS (see: http://www.hse.gov.uk/construction/cdm.htm and http://www.cskills.org/supportbusiness/healthsafety/). These resources provide an overarching working guideline for DfS practice. However, the procedures for DfS do not show how risks can be identified, addressed and monitored using specific measures in detail. Moreover, they are only paper-based guidelines and manuals for DfS. On the other hand, under the category of tools for risk identification during DfS practices, Hinze & Marini (2008) developed around 400 design suggestions, which were incorporated into a computer design toolbox, and Cooke et al. (2008) introduced a web-based system called ToolSHeD to help designers assess the level of fall risks in their design choices for roofs. The issue of risk identification and evaluation has been a particular focus of the second category, DfS tools, which provide a whole and more specific set of risk issues that can be addressed in the design stage. However, they do not really establish a safe design framework but serves as a supplement to existing frameworks. Very recently, building information modeling (BIM) tools have been developed to provide designers with DfS assistance (Zhang et al. 2013). Because BIM is still in the infantry stage of implementation in the industry, its high level application for DfS would require more time.

5. DEVELOPING A MOBILE KNOWLEDGE MANAGEMENT SYSTEM FOR DfS

It could be safety argued that designers would need an easy-to-use and economical DfS support resource, given the complex nature of the design process and the cost and time constraints design firms face. Recent advances in mobile computing technologies offer unique opportunities for developing cost-effective, novel knowledge management systems for the construction industry. The management of knowledge made possible by mobile computing devices (e.g. PDAs, Smartphones & iPads), together with mobile Apps, has critical aspects that best suit and appeal to designers as they can provide anytime, anywhere access to contents, just-in-time support and a media-rich interactive environment (Acar et al. 2008). Many construction-specific mobile Apps are already in use, ranging broadly from specific purpose calculators to design, collaboration and site monitoring tools (Mike 2011; ConstrucTech 2011). In contrast, and despite this proliferation, the potential of mobile computing technologies for accident prevention through design has not yet been explored. Hence, this section elaborates on the conceptual development of a new mobile App that can assist designers in reducing the high toll of construction accidents by prevention through design.

The conceptual design of the proposed mobile App includes a DfS knowledge map and mock-up layouts or wireframe diagrams. The knowledge map represents the logical layout of DfS knowledge and information for easy use by designers while the wireframe design outlines the placement of text, images, and buttons. These, together, conceptualize the proposed mobile App.

Fig. 3 illustrates the DfS knowledge map for fall prevention through design, a demonstration case. This was developed based on the findings of detailed content analyses of related documents and literatures, and comprises the design solutions needed for fall prevention through design. The map outlines the building elements considered for fall prevention and then detailed design solutions for one of the elements, roofing, are described.

Fig. 4 illustrates the wireframe mockup of the proposed mobile App. A number of wire framing tools are available for creating mockups and clickable mobile App simulations. Examples include Axure, Balsamiq, Fluid, Justinmind, Mockflow, Moqups, Proto.io, Protoshare, UXPin Wireframe. This mockup was created using UXPin.

6. CONCLUSION AND THE WAY FORWARD

DfS is regarded as an effective means to curtail workplace accidents on construction sites as it eliminates hazards at source. Designers face numerous challenges in effectively implementing DfS in their design practices owing to their limited knowledge on construction safety. This research has demonstrated how a mobile App can be developed to assist designers in accident prevention through design. Nonetheless, the paper discussed only the design part of the mobile App. Further research is underway to test the effectiveness of the new mobile App to support effective DfS analyses. In conclusion, the implementation of the new mobile App, after testing, could foster enhanced DfS implementation in industry and thereby accident reduction in construction projects.

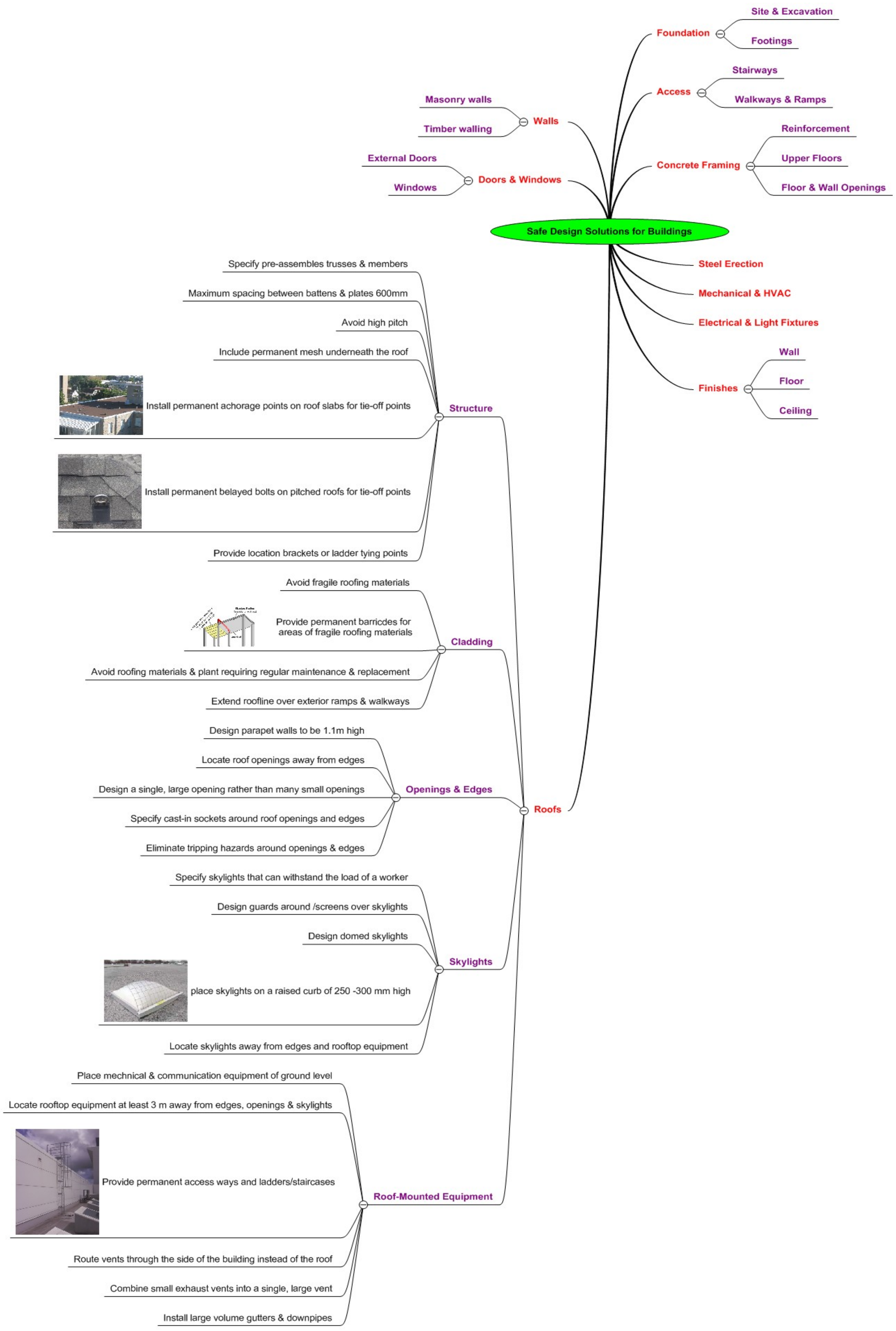


Fig. 3: Knowledge mapping for fall prevention through design

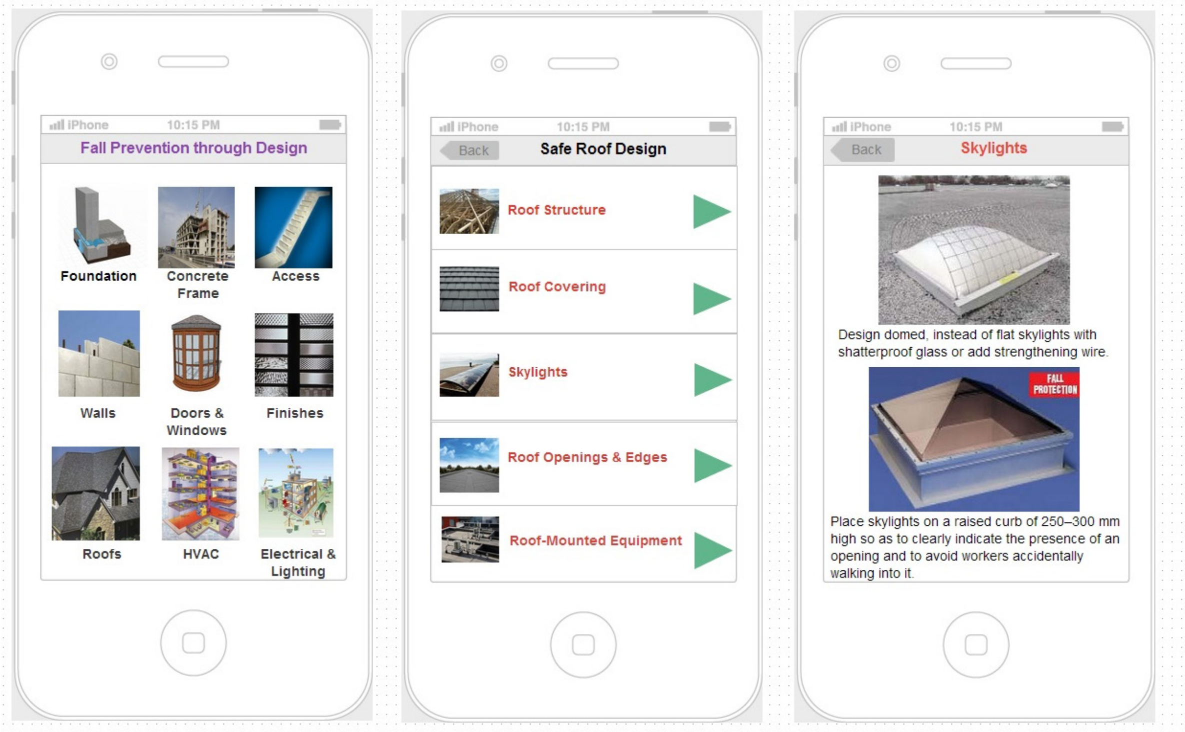


Fig. 4: Mobile App mockup for fall prevention through design

7. REFERENCES

Acar, E., Wall, J., McNamee, F., Carney, M and Öney-Yazici, E. (2008). Innovative safety management training through e-learning. *Architectural Engineering and Design Management* 4 (3), pp. 239-250.

Behm, M. (2005). Linking Construction Fatalities to the Design for Construction Safety Concept. *Safety Science* 43(8), pp. 589-611.

Bureau of Labor Statistics (2010). Census of fatal occupational injuries summary 200’, *Economic News Release*, www.bls.gov/iif/oshcfoi1.htm [10/02/2012]

ConstrucTech (2011). *Construction apps extend functionality*. http://www.constructech.com/news/articles/article.aspx?article_id=8864. [9 Jan 2012].

Cooke, T., Lingard, H., Blismas, N. and Stranieri, A. (2008). ToolSHeDTM: The Development and Evaluation of a Decisive Support Tool for Health and Safety in Construction Design. *Engineering, Construction and Architectural Management* 15(4), pp. 336-351.

Creaser, W. (2008). Prevention through Design (PtD) Safe Design from an Australian Perspective. *Journal of Safety Research* 39(2), pp. 131-134.

Fadier, E. and De la Garza, C. (2006). Safety Design: Towards a New Philosophy. *Safety Science* 44(1), pp. 55-73.

Gambatese, J., Behm, M. and Hinze, J. (2005). Viability of Designing for Construction Worker Safety. *Journal of Construction Engineering and Management* 131(9), pp. 1029-1036.

Gibb A, Haslam R, Hide S and Gyi D. (2004). The role of design in accident causality, In Hecker S, Gambatese J & Weinstein M (Eds), Designing for Safety and Health in Construction: *Proc., Research and Practice Symposium*, UO Press, Eugene. pp 11-21.

Health and Safety Executive (2010). *Statistics on fatal injuries in the workplace 2009/10*. http://www.hse.gov.uk/statistics/fatalinjuries.htm [10/01/2012]

Hinze J and Marini J. (2008). *Software to select design for safety suggestions*, http://www.irbnet.de/daten/iconda/CIB10265.pdf. [9 Nov. 2009].

Hinze, J. and Wiegand, F. (1992). Role of Designers in Construction Worker Safety. *Journal of Construction Engineering and Management* 118(4), pp. 677-684.

Hu K, Rahmandad H, Smith-Jackson T and Winchester W. (2011). Factors influencing the risk of falls in the construction industry: a review of the evidence, *Construction Management and Economics* 25(3):397-416

Labour Force Survey (2009). *Safety and health for the construction industry*, http://www.statistics.gov.uk/CCI/Nscl.asp?ID=5316&Pos= 2&ColRank=1&Rank=80 [11/10/2010]

Mike, N. (2011). *How mobile apps changed the construction industry*. http://www.onthegoware.com/mobile/mobile-apps-changed-construction-industry. [9 Jan 2012].

Mroszczyk J.W (2008). *Designing for construction worker safety*, www.asse.org/membership/docs/John%20Mroszczyk%20Article.doc. [24/4/10]

Rechnitzer, G. (2001). *The Role of Design in Occupational Health and Safety: A Discussion Paper*. Safety Institute of Australia, Melbourne.

Safe Work Australia 2011, *Construction fact sheet*, http://safeworkaustralia.gov.au/AboutSafeWorkAustralia/ WhatWeDo/Publications/Pages/ FS2010ConstructionInformationSheet.aspx [05/01/2012]

Spiteri, C and Borg, J. (2006). Towards a conceptual framework for mobile knowledge management support, International Design Conference – Design 2006, Dubrovnik, Crotia, 15-18 May, pp.1-8

Szymberski, R.T. (1997). Construction Project Safety Planning. *Tappi Journal* 80(11), pp. 69-74.

Toole, T.M. and Gambatese, J. (2008). The Trajectories of Prevention through Design in Construction. *Journal of Safety Research* 39(2), pp. 225-230.

Zhang, S., Teizer, J., Lee J.K, Eastman, C.M and Venugopal, M. (2013). Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules. *Automation in Construction* 29(1), pp. 183-195.

IMMERSIVE CONCEPTUAL DESIGN IN A 3D CITY MODEL

Andreas Lippold

Autodesk, Germany

ABSTRACT: *Facing the challenges of aging infrastructure, the search for better renewable energies and growing population in cities, Government agencies, municipalities and utilities are looking for more accountability, risk mitigation and collaborative decision making around investments in infrastructure design and construction. Often, what's requested by stakeholders is a better overall process to understand, experience, and collaborate around infrastructure development while balancing the demands for sustainability with the need for economic growth and livability.*

For many stakeholders, an accurate 3D city model can help design professionals, agencies, and public stakeholders alike understand the impact of projects more intuitively than can 2D plans. The visually immersive presentation and interaction (interactive 3D navigation, manipulating, annotating, publishing, collaborating and distributing information "on-demand") of 3D models can help to meet these challenges.

Infrastructure planning processes typically involve several parties, from designers, agencies, and public stakeholders. Collaborative processes require that information is available from different platforms at any time. Collaboration includes the ability to markup and comment so that reviewers can share feedback with designers, as well as the ability to allow teams to improve efficiency by distributing design across communities of editors. Cloud-centric workflows enable users to enhance the process of collaboration throughout the planning process, such as comments and collaboration, in order to achieve a more confident and sustainable decision on infrastructure design and construction. This means being able to pass information, connect to the team or doing editing work on the same dataset using the internet connection to reach the model stored in the cloud. Moreover, 3D models enable all stakeholders to stay on the same page regarding proposed development, because of the more natural, intuitive way for communicating with non-technical stakeholders.

Besides the collaborative environment the way those 3D models are visualized are important in terms of acceptance. Based on even simple GIS and CAD data the look and feel should be as realistic and immersive as it can represent the reality as it is or as it can be.

KEYWORDS: *infrastructure design, conceptual design, 3D sketching, Cloud-centric workflows, Collaboration, 3D modeling, immersive visualization*

1. INTRODUCTION

Infrastructure projects are all around us and affect people every day. Planning new or enhancing existing infrastructure assets or networks becomes a more and more complex job then in the past. What makes it so complex and why are we facing so many projects nowadays? This paper looks at the reasons and challenges of today to find out where exactly virtual 3D model applications can help to design and evaluate infrastructures before they get build. Autodesk provides tools for the AEC market and launched the BIM concept throughout the Architecture world. With Autodesk® InfraWorks™ (Fig.1) we are looking at tools which provide the BIM concept for infrastructure projects in order to cope with the raising demand to modernize our urban infrastructure world.

Citation: Lippold, A. (2013). Immersive conceptual design in a 3D city model. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Fig. 1: So where is the need of rebuilding and offering of new infrastructure coming from and what are the challenges which are faced by tackling today's infrastructure projects?

1.1 Exponential Urbanization and scarce fossil fuel resources boost Infrastructure Investment

Buildings, utilities, and transportation systems are facing a tremendous challenge from the exponential growth of urban population as well as an increased use of renewable energies over fossil fuels. Aging infrastructure is an issue occurring everywhere from underdeveloped countries up to the leading economies of the world. Government agencies, municipalities and utilities are looking for accountability, risk mitigation and collaborative decision making around investments in sustainable infrastructure design and construction. With respect to the amount and complexity of today's infrastructure projects as well as the anticipated short time frame for their realization there is a strong need for effective tools and data management throughout the life cycle of infrastructure projects.

Providing proper tools and services, organizations will need to look at infrastructure business trends and the resulting challenges.

1.1.1 Population growth and urbanization

"The World Economic Forum estimates that we will have to build the same urban capacity (housing, infrastructure and facilities) in the next 40 years that we have built over the past 4,000 years in order to meet the demand arising from this unprecedented urbanization." (Geoff Zeiss 2012). This indicates a tremendous demand and the need to develop and maintain infrastructure at an unprecedented scale. According to United Nations Population Fund more than half of the world's population is living in towns and cities. "By 2030 this number will swell to almost 5 billion, with urban growth concentrated in Africa and Asia. While mega-cities have captured much public attention, most of the new growth will occur in smaller towns and cities, which have fewer resources to respond to the magnitude of the change." (UNFPA 2007)

1.1.2 Sustainability: New ways of energy generation and distribution

Sustainability crosses nearly every section of human activity today which is affected by energy consumption.

Within urban regions where thousands of people live energy plays an important role. With fossil fuel resources becoming scarce and the continued shift from nuclear power, the general consensus is that we need to find new ways to generate energy. Looking at solar power plants and wind parks on one hand and the existing infrastructure on the other, it is obvious that those networks need to be replaced to cope with all of the new energy resources, including the location of these resources relative to the populations they serve (e.g. often wind farms are located far from the cities they serve).

Scare resources are more or less a kick off to look at more resilient energy distribution and overall operational cost effective energy production. At the same time the result should be a much cleaner environment where new infrastructure integrates smoothly into.

1.1.3 Large investment in infrastructure

The biggest problem is the financial investment to maintain existing and develop new infrastructure in a way that the investment turns into sustainable environmental, economic and social growth. Many countries spend huge amounts of money to stimulate their respective markets. In 2012 Germany alone spend \$33.3365M for Infrastructure out of \$3.006.800M GDP (CRP 2013). "Just keeping pace with projected global GDP growth will require an estimated \$57 trillion in infrastructure investment between now and 2030. That's nearly 60 percent more than the \$36 trillion spent over the past 18 years…" (McKinsey 2013)

As shown above there is a strong need to invest in infrastructure projects to compete against the pressure arising from urbanization and changing energy paradigms. “Getting it right with cities and infrastructure has significant potential, not just from a pure economic perspective, but also from a social and environmental sustainability perspective. Getting it wrong is likely to be very costly socially and environmentally” (Ken Henry 2010)

Let’s have a quick look at the resulting challenges, which drive the requirements for virtual reality applications.

1.2 Business challenges

The key business challenges in all of this is that organizations need better processes to understand, experience, and collaborate around infrastructure development while balancing the demands for sustainability with the need for economic growth and livability. Stakeholders are dealing with a situation where project requirements are increasing while budgets decrease. To address these challenges organizations must enhance coordination and collaboration efforts by utilizing the cloud and open access to data.

1.2.1 Increasing project requirements with shrinking budgets

Projects are much more complex but require planning and decision making based on various requirements in a short time. This as well as shrinking budget, puts many AEC firms in the position whereby they are using the latest technology to drive productivity and handle the complexity of infrastructure projects.

1.2.2 Centralized Data

As mentioned above the complex structure of projects in the infrastructure domain relates to different kind of data. It is essential that every necessary data set is accessible to stakeholders working on a project. Centralized storage for the most updated version of a dataset provides fast access and can be used for meaningful analysis and decisions early in the planning phase of any project.

1.2.3 Efficient coordination and collaboration

Efficiency throughout the entire life cycle of an infrastructure process is mostly based on coordination and collaboration. Stakeholders must be on the same page from day one and communicated with in light of project proposals. Visual deliverables can address costly design conflicts, milestones, schedules and versions before the construction begins.

Infrastructure planning processes typically involve several parties, from designers, agencies, and public stakeholders. This anticipated collaboration means that information is available from different platforms at any time. Bent Flyvbjerg points out that mostly misinformation within complex infrastructure projects cause a tremendous deviation to the originally cost estimate. Within his researches he found out that nine out of ten projects have a cost overrun, where this relates to twenty nations across all continents and did not improve over the seventy-year period covered by the study (Flyvbjerg 2005).

Streamlining the whole workflow to be more effective makes a lot of sense. “It will be necessary to speed up approval processes, invest heavily in the early stages of project planning and design, and structure contracts to encourage time and cost savings (McKinsey 2013). It needs tools to provide those workflows which are capable of it. Building Information Modeling has been successfully established in the architecture domain – can this be an approach for infrastructure?

2. BIM FOR INFRASTRUCTURE

3D visualization is a more natural, intuitive medium for communicating with non-technical stakeholders as Geoff Zeiss pointed out. A realistic 3D model can help design professionals, agencies, and public stakeholders alike understand the impact of projects in a far greater way than that of 2D plans.

Building Information Modeling (BIM) describes workflows for creating an electronic model – in 3D – of a facility for the purpose of visualization, engineering analysis, conflict analysis, cost engineering, budgeting and many other purposes (Fig. 2).

“Engineers and owners developing infrastructure projects are facing unprecedented challenges—lower project funding, design complexity, economic uncertainty and public resistance to major infrastructure projects. Expanding our Building Information Modeling solutions for infrastructure can help our customers in transportation, water, energy, and land development segments to overcome these challenges—saving time and money and improving margins on projects,” said Paul McRoberts, vice president, infrastructure product line group, AEC solutions, Autodesk.

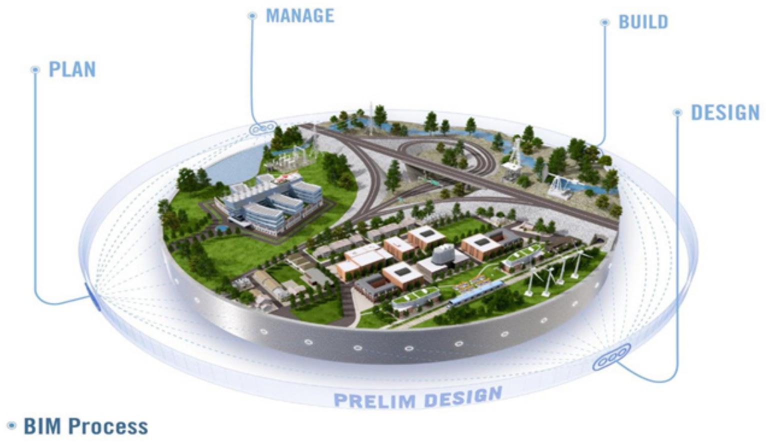


Fig. 2: Infrastructure Life Cycle, Autodesk

Increasing productivity for a much better and faster decision making will be facilitated through the combination of geospatial and 3D technology as well as BIM to rehabilitate the aging infrastructure.

3. HOW SOFTWARE CAN HELP TO OVERCOME THE PLANNING AND MANAGING DIFFICULTIES WITHIN INFRASTRUCTURE PROJECTS

Effective planning and design saves time and budget, seeds trust in the decision and communicates with a broad group of stakeholders. Let's look at some features that can be used to help overcome the challenges of planning, designing, constructing, and managing infrastructure.

Big Data

When working with and in 3D models the amount of data is significant higher than found in most 2D drawings. Depending on the Level of Detail, the spatial extend and visual effects infrastructure model sizes reach GB of data, which needs to be handled efficiently.

Apart from the classical Desktop application with a good set of hardware settings we are looking at a totally different landscape today. As a stakeholder, designer, project manager or planner I want to be able to access from and publish my model to different clients (Web, Tablet, Desktop, Smartphone) on different platforms (Win, IOS, Android…). I also want to manage my model content, such as rules, styles, models from anywhere I have access.

So, how does this help with the challenges mentioned above?

If all project related content can be handled across the project team in a way that size does not matter work can be much more efficient. There won't be version of something except the model, which is the base of all decision making. This needs the willingness of providing the data at a central place.

Integrative BIM for infrastructure

BIM for infrastructure deals with assets from the architecture, engineering, construction and GIS worlds. In terms of an integrated process BIM ensures that data and metadata can be shared throughout the infrastructure life cycle from conceptual design, through detailed design and construction as well as operation and maintenance.

So, how does this help with the challenges mentioned above?

When creating a new design one usually keeps initial drawings until new designs take their place. Once a design is accepted it can be easily transferred into another tool (AutoCAD Civil 3D or Autodesk Revit) for the detailed design. All relevant information can now be accessed and detailed can be added. The output of the detailed design phase typically includes a 3D infrastructure model from Autodesk InfraWorks that can be used to validate designs created via other design tools, like Civil 3D or Revit.

The benefit of this integrated model-based design approach for infrastructure is that rich information can be created and shared from the beginning without recreating content.

Easy to use, workflow/persona based

The user experience is one key to success as it describes how a user interacts with an application in order to get work done in a more efficient way. Currently, most professional software for planning, designing, and managing infrastructure is of the monolithic desktop variety and can only really be used by trained professionals. Since time and money are the limiting factors planners, stakeholders and designers need to be able to enter workflows and content which are appropriate to their work as well as from anywhere no matter if they sit in front of the desktop or on their way with a tablet – via a simple user experience.

So, how does this help with the challenges mentioned above?

Different personas within a project have different focuses. Most of them will never use all of the functionality the professional software provides or nor will they use the best and effective workflow since the software's user interface likely does not make it easy for them to do so. The answer: imagine a designer logs into a cloud-based system and based upon his credentials the software ecosystem knows establishes his/her identity and role as well as which content and functionality maps to that designer helping them get their work done more effectively.

Using cloud for services, communication (sharing, feedback) and collaboration

Infrastructure projects are much more networked than any other time in history. Decisions need to be made based on the same information across distances and disciplines. Distributed teams must be able to collaborate without sending copies around, further replicating data that is already out of date.

In our private daily lives we use cloud technology to connect to people, store and share information, stream music and videos, as well accomplish other tasks that are difficult without being connected. Technology provides huge potential to spread work, date and tasks across the network to the people who need that information. Infrastructure planning ideally participates from cloud centric workflows to ensure that all stakeholders are kept up to date.

Communication is the key to this and is also where infrastructure modeling starts. If a model is stored in the cloud and can be reached from different stakeholders, everyone is on the same page and can contribute by giving feedback, marking certain issues or even creating new content.

A second huge potential of the cloud is the idea that it can provide services that perform tasks more efficiently than humans can on solitary desktop machines. Resources can be used which are not at your reach in order to provide a simulation or analysis no matter which device you are using.

So, how does this help with the challenges mentioned above?

Staying on the same page using an always up to date model and having the chance to directly stay in contact with team members is a priceless advantage in investing the rare time and budget more efficiently. Cloud-centric workflows enable the users to enhance the process of collaboration throughout all stages of the planning process, such as comments and collaboration, in order to achieve a more confident and sustainable decisions. Moreover, 3D models enable all stakeholders to stay on the same page regarding proposed developments.

Create parameterized conceptual design

Infrastructure projects are of big interest in general. There are many dependencies where projects can fail, as explained in the aforementioned examples. Nearly every one of us plays a role in construction projects when stepping out of the door each morning. This means that stakeholders within a project are so divers in consuming the ideas about what "can be" that it would take ages to communicate in a proper way to every involved group. As mentioned before a 3D representation of the world outside drives a common understanding of we know and look at a 3D model evokes a more natural understanding of proposed changes in the existing world.

The "what can be" is now evaluable compared to the existing infrastructure to all stakeholders also the non-technical. In this case 3D is the rule.

In the conceptual planning stage you would want to set certain parameters to get assumptions according to project related requirements, for example sketching a road. The way a road needs to be designed depends on the assumption if it behaves as a highway or a local road towards its angles, slope and rise. Perfectly a designer would choose a road type where previously set parameters from local requirements are defined, which helps him to sketch within these boundaries (Fig. 3).

So, how does this help with the challenges mentioned above?

Again, looking at the constrains of a small budget, less time, complexity and addressing diverse stakeholders the first sketch should be quick, representable and according to local or project requirements. This workflow prevents project members to recreate content to communicate, adjust proposals to assumptions manually and dumping time and money to create a proposal.

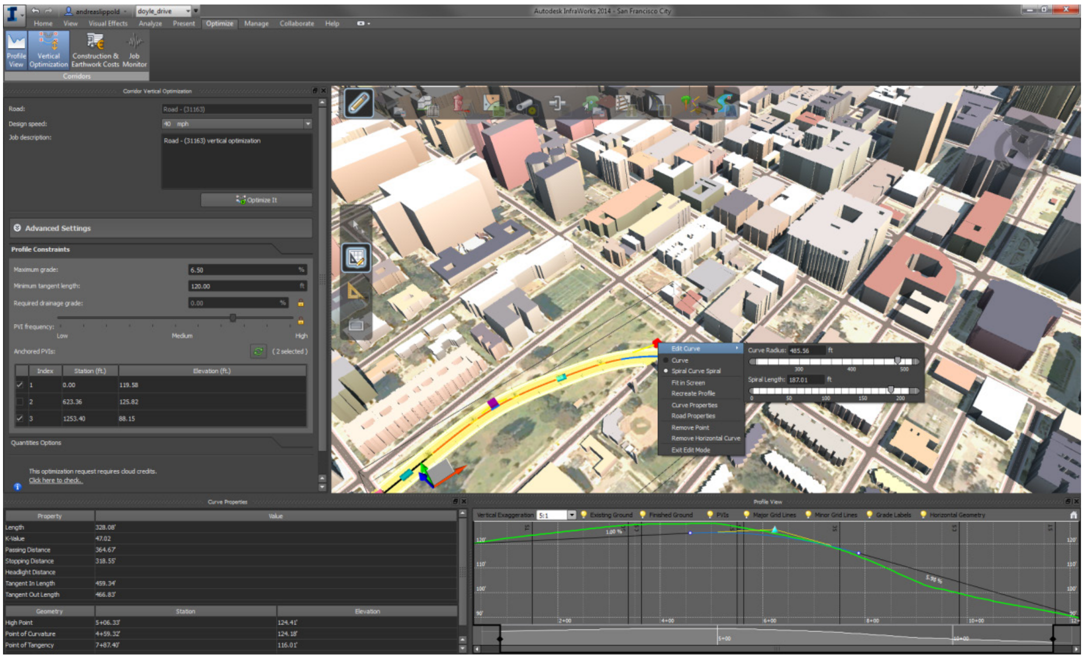


Fig. 3: Designing a civil road in InfraWorks 2014, Autodesk

Immersive visualization

Besides the collaborative environment the way those 3D models are visualized are very important in terms of acceptance. Based on even simple GIS and CAD data the look and feel should be as close to realism as it can be to get the impression of "what will be" in the context of is already there.

There are two ways to provide a realistic look and feel of a virtual 3D model. On one hand a building for example can be visualized as a simple block in order to capture the 3D building extend. Shaping out the details of a building in terms of façade, roof and even interior design can drive the acceptance for a planning because of the detail or lets the viewer recognize where he is located by realizing the context by its details. On the other hand it depends much on the correct light, reflections and realistic behavior of nature (sky, water) to wash-out away the borders between the virtual world and reality. A realistic representation is shown in the example of San Francisco in Fig. 4.

Fig. 4: Downtown of San Francisco in InfraWorks 2014, Autodesk

So, how does this help with the challenges mentioned above?

Infrastructure projects are successful if they are accepted broadly. This results out of a good communication with all stakeholders, right from the beginning based on an immersive and realistic 3D infrastructure model. It certainly make a difference if you see a blue polygon where the label says it is a water areas or if you see a water shaded surface where the sun and other infrastructure assets are reflected. It makes a difference if you see a gray block or a block with light maps and shade to represent a cube in a realistic environment and time.

The understanding and acceptance rises if stakeholders face something more realistic and not game like. The benefit for the project lays in the shorter decision making phase since all anticipated groups and stakeholders are informed in a natural way by a representative 3D model to understand, discuss and evaluate the early design.

4. AUTODESK® INFRAWORKS™

The introduction of BIM has changed the way architecture companies work. With BIM for infrastructure Autodesk is going to address the whole AEC world lifting the BIM approach to the scale of infrastructure projects to face the above mentioned challenges.

With Autodesk InfraWorks AEC firms can"…quickly and easily create infrastructure design models. Accelerate the design process, and enhance understanding of project constraints for better decisions. Generate data-rich proposals to better predict how design alternatives may perform in the existing environment and more effectively communicate with stakeholders" (Autodesk.com).

Today InfraWorks enables the user to model existing infrastructure form CAD, GIS and 3D model data and visualize them in a realistic way.

Powerful design tools provide the option to sketch out early design proposals which can be verified and exported to AutoCAD Civil 3D.

The visual appealing proposals can be shared through the cloud in order to work collaboratively on a project, publish scenarios through I-Pad and Web viewer as well as create videos based on various options to run through your model and pop up information as you go.

This short summary of Autodesk InfraWorks shows how a tool may help to create and communicate complex infrastructure projects easily in a visually understandable way and share it across tools, platforms and stakeholders. To cope with complex projects in a short time and deliver output to various interest groups and internal project workers AEC firms need a set of tools which easily adopts to certain workflows and roles in order to be efficient and fast. This cannot be accomplished by a monolithic desktop solution rather than an ecosystem out of services, application and toolsets.

InfraWorks is a new invention and needs to prove if the concept reaches the industry in the way it is meant to be. The feedback so far from the civil engineering companies shows a strong adoption of InfraWorks since they are able to sketch out a detailed idea easily as well as using the initial design further on within the detailed design phase. Today the key element to success hereby is the way to create a design in 3D based on certain assumptions very quickly and being able to communicate this broadly. Current CAD application cannot provide the context (large scale), cannot offer a quick concept sketch and providing a natural view on things is rather tough to generate.

Looking ahead InfraWorks should be able to address different assumptions which come along with a new design and need to be analyzed or simulated within the new planning's context. It does not make much sense if a proposal looks good but based on the given constrains and requirements it cannot be build. If this pops up in the detailed design phase then the project ends up as we can see it in many present examples, costs will explode and time will pass. Starting already today with cloud based services to calculate optimized profiles, or setting rules and constrains for certain road types is the way InfraWorks gets enhanced in the future to make sure a proposal gets as solid as it can get to be built under the acceptance of all stakeholders.

When looking at InfraWorks we do see an ecosystem of tools which provides a platform for Stakeholders, Planners, Civil engineers and everyone who is involved in infrastructure changes. There shouldn't be a monolithic desktop providing unlimited functionality rather than only the tools which are needed to slim the process of creating, analyze, simulate or present content.

5. SUMMARY

Facing a tremendous demand of extending and building new infrastructure today, the expectations on tools have changed. 2D sketches and plans are consumable by only a certain group of professionals. Technically not so skilled stakeholders need to have a different view on things they see within the 2D plan. The public is more engaged when it comes to bigger infrastructure projects and wants to take part in it, want to explore it.

3D city models have become a part in city marketing and municipalities are more often considering those models to be part in a decision making and informing process.

Given the short timeframe and the smaller budget planning has to be faster, more efficient and easy to understand by various stakeholders in order to achieve the best possible design, without entering a redesign phase later in the project.

Complex infrastructure projects designed and handled in 3D, data size matters when it comes to share simulate or analyze. Cloud centric workflows are perfect when it comes to highly intense tasks which can hardly be solved on a single desktop. Making a model available to the whole group involved in the project across distances can be tough without a cloud storage which intelligently synchs and provides easy access to the model, to the group and the content.

The main challenge in today's infrastructure world is to save time and money during decision making without leaving stakeholders outside of the process. Autodesk® InfraWorks™ today shows how a software ecosystem can easily be used to create a model where planning is made upon. Initial planning process need to be in 3D to reflect as realistic as it can the new scenario to a wide group. Parameterized sketching with highly realistic styles are used to create the scenario very quickly as well as sharing it right away.

These are the credentials to come up with a quick idea to be evaluated throughout a stakeholder community with respect to shorten the process of creating different proposals as well as deciding on certain proposals. This can save time and money, because everyone is on the same page and the detailed planning stage can be entered with a properly evaluated design which does not need a recreation from sketch.

BIM for Infrastructure can be the process to align the whole workflow of an infrastructure life cycle and applications like Autodesk® InfraWorks™ are providing some of the functionality already today.

Looking ahead, 3D will be the way to go. On top of a growing number of 3D city models there will be different kinds of applications to plan, to publish, to analyze and to simulate as well as making it easy to collaborate on a model. In order to cover all functionality you will need the internet technology to provide services, request for calculation power and connecting to your stakeholders. It will be a strong shift from monolithic desktop solutions towards an ecosystem of tools that enforces project planers intuitively do their work in a natural but professional way.

6. REFERENCES

CRP (2013). http://www.crp-infotec.de/01deu/finanzen/bundeshaushalt_aktuell.html

Flyvbjerg (2005). Policy and planning for large-infrastructure projects: problems, causes, cures; Environment and Planning B: Planning and Design 2007, volume 34, pages 578 – 597;
http://papers.ssrn.com/sol3/papers.cfm?abstract_id=2230414

Henry, Ken (2010). To Build or not to Build: Infrastructure Challenges in the Years Ahead and the Role of the Government: Address to the Conference on The Economics of Infrastructure in a Globalized World: Issues, Lessons and Future Challenges;
http://archive.treasury.gov.au/documents/1763/PDF/Infrastructure_Conference.pdf

McKinsey (2013). Infrastructure productivity: How to save $1 trillion a year,
http://www.mckinsey.com/insights/engineering_construction/infrastructure_productivity

McRoberts, Paul (2012). BIM for Infrastructure, Infrastructure Product Line Group, Autodesk

UNFPA (2007). Urbanization: A Majority in Cities, http://www.unfpa.org/pds/urbanization.htm

Zeiss, Geoff (2012). Convergence, interoperability and standards, Autodesk,
http://www.opengeospatial.org/blog/1591

THE DESIGN SPACE EXPLORATION ASSISTANCE METHOD: CONSTRAINTS AND OBJECTIVES

Fabian Ritter, Philipp Geyer & André Borrmann
Technische Universität München, Germany

ABSTRACT: *In the early design stages of buildings, architects cope with a multitude of decisions that affect the later performance of the building. Most of these decisions have a fundamental impact on the building design; later changes are impossible or require a very high effort. When taking these decisions, numerous constraints and objectives have to be considered. With today's mainly manual design workflows, only very few design options can be elaborated and evaluated against the various performance criteria. In consequence, the design space (the space of all possible design options) is explored only to a very limited extend and finding a good solution depends strongly on the experience of the designing architect. To cope with this issue and to better support architects in the early design stage, we are developing the Design Space Exploration Assistance Method (DSEAM). The method aims at applying techniques of advanced computation to provide comprehensive information and design options. To provide a sound foundation for this method, this paper investigates how relevant and evaluable the individual objectives and performance criteria are. In addition, we discuss the importance of geometric constraints in building design and describe an approach which allows architects to define them in an intuitive interactive graphical manner.*

KEYWORDS: *Design Space Exploration, Conceptual Design, Optimization, Decision Making*

1. INTRODUCTION

In the last decades, the design of new buildings has become an increasingly complex process, in which different goals have to be fulfilled involving various experts. Whereas before only functional criteria and the appearance of the building were criteria, nowadays the focus shifts to energy efficiency and sustainability. The designer needs to take into account resource consumption and a lot other technical criteria during the design process. In this context, designing a building is a highly complex and challenging task, that interconnects architectural design closely with engineering. A well-designed building has to meet many different requirements, i.e., it must be a solution that fulfils its function well, has good appearance and spatial qualities, has a sound structural system, provides a pleasant indoor climate, has an energy and resource efficient design and complies with the clients requirements such as cost budget. Accordingly, the building design process is of complex nature involving a large number of decisions and iterations.

Today this complex decision-making process is mainly conducted informally and on the basis of experience, often resulting in sub-optimal solutions. If, however, computer tools assist the process, better performing design options may be found. Such assistance has the highest impact in the early design stages, where fundamental decisions are taken and modifications are easy.

Though many research projects in the field of assisting conceptual design by design space exploration (DSE) have been performed in recent years, the developed approaches did hardly find their way into industry practice. This is mainly due to the fact that most of the available tools are complex, require a deep mathematical understanding, and can thus not be intuitively operated by architects.

To cope with this issue, an approach to integrate expert engineering knowledge into architectural conceptual design, the Design Space Exploration Assistance Method (DSEAM), is proposed in this paper. DSEAM helps architects to systematically investigate different design options and find well-performing solutions. This is achieved by providing means for evaluating preliminary designs with respect to design objectives, such as structural performance, energy and resource efficiency, and integrating an automated design space search, which provides suggestions for improving the design.

This paper tackles the translation of the technical and functional requirements, design intentions as well as the criteria of sustainability into computable models in order to allow the automated search. In this paper, the criteria of the DGNB (Lemaitre C. and Deutsche Gesellschaft für Nachhaltiges Bauen 2012) provide the basis, however,

---

Citation: Ritter, F., Geyer, P. & Borrmann, A. (2013). The design space exploration assistance method: constraints and objectives. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

having in mind the translatability to other criteria systems, such as LEED (2009) or BREAM (2008). This translation requires the formulation of requirements and intentions as objectives or constraints. However, those models are by far not able to capture all relevant criteria. Therefore, different strategies of interactivity are required to manage the criteria. For some, e.g. energy consumption and related cost, an automated search works well as they depend on simple physical interdependencies such as thermal transmission through insulation. For other, e.g. the distance of columns in a building structure, an interactive approach is required as there are functional considerations of the use in the building and of the appearance of the façade determined by the column grid. This decisions only an architect is able to carry out, because it relies on tacit knowledge which cannot be described explicitly.

Therefore, the paper first examines typical constraints following a common course and interactive character of a design process. Second, the translation and evaluation of criteria of sustainability aims at proving assistance for sustainable design. As a representative method, this paper uses multicriteria design optimization for developing the DSEAM. Furthermore, as proof of concept, a prototypical software tool has been implemented which provides an intuitively usable, interactive interface as part of an existing and commonly used design environment.

In the first step, the tool supports the design of regular office and administrative buildings. There are two reasons for this decision: On the one hand this kind of buildings normally have a regular shape. The building itself as well as the office spaces are often of rectangular shape. On the other hand, there exist many regulations for these kind of buildings, like working space guidelines, fire safety regulations and specific green building certificates like LEED, BREAM and DGNB, which are examined in this paper.

2. STATE OF THE ART

Automation approaches applied for DSE in research and application in building design are either general studies for building types that do not consider the specific situation of the individual design case with its environment; or there exist specifically tailored solutions for single design case instances.

For example, the computer program Rt by Mahsuli and Haukaas (2013), that focus on multi-model analysis, addresses the need for tools to carry out modern reliability and optimization analyses.

The H.D.S. Beagle 1.0 is a tool developed by Gerber et al. (2012) that combines parametric modelling (Autodesk Revit 2013) with energy analysis (Autodesk Green Building Studio 2013) and cost prediction (Microsoft Excel 2013) in a genetic algorithm (GA) optimization. Another tool on the basis of Autodesk Revit is the Design Performance Viewer developed by Schlueter and Thesseling (2009).

Gane and Haymaker (2012) have developed a new method, the Design Scenarios (DS) to collect and manage the requirements of multiple stakeholders to enable an alternative generation, analysis and decision making process on the basis of parametric CAD tools.

A method to convert set grammars into parametric models and calculate their energy demand is presented in Granadeiro et al. (2013). With this approach, many different shapes of a building can be generated automatically and then be translated into a simulation model to calculate energy demands.

Mensinger et al. (2012) developed a tool using GA to generate and optimize steel and steel composite structures in terms of sustainability. Fernandez-Ceniceros et al. (in press) have developed a model to for finding the best one-way floor slab design regarding embodied CO2 and cost including construction and transportation costs. Shi & Yang (2013) coupled Rhinoceros/Grasshopper with the performance simulation programs Ecotect, Radiance and Energy Plus to establish the workflows for performance-driven architectural design and optimization.

A framework for automated LEED certification based on cloud-BIM is presented by Wu et al. (2012). They propose to couple BIM-software and mobile BIM-apps to a central Multicore BIM Server to automatically extract the necessary information to load it on the LEED Automation Cloud.

A framework that copes with a multilevel optimization is the Bi-Level Integrated System Synthesis (BLISS, Sobieszczanski-sobieski et al., 1998). This hierarchical approach of using optimization provides foundation for partial optimization problems within user interaction.

Despite these important research works, an approach that assists architects with finding well performing solutions in the early design stages is still missing. A methodology is required which allows to assess initial building designs with respect to energy efficiency and sustainability. Corresponding assistance methods have to be available right in the design tool they use for modelling the geometry and further building information. It has to combine the manual design space exploration with assisting optimization approaches presenting well performing solutions to the architect to explore the design space and to decide on the solution. These optimization approaches will be strongly related on existing methods; only few will be implemented newly. The new method focuses on providing the methods in the design tool. Nevertheless, the Building Information Modelling (BIM) process will be supported through making the results of the DSEAM available to serve as a basis for discussions between the involved designers and engineers and further refinement in downstream applications.

3. ASSISTANCE IN THE WORKFLOW

Assistance in the workflow means that the computer tool, i.e. optimization does not prescribe the "optimal" design solution but gathers information on well-performing solutions to allow the designer to select from. There are two major reasons, why not just one best solution is demanded; on the one hand, the automatic generation and search of the well performing solutions has to be fast. On the other hand, an optimization is not able to find the real optimum, because not all relevant objectives can be integrated directly due to tacit knowledge and non-numerical criteria. Maybe the optimum design for the whole building not includes the optimum design of e.g. the structural materials because of interactions to other disciplines. So only with the fast feedback of well performing solutions, the architect can explore many different variants and therefore will find the overall best performing design.

We see this process as a hierarchical optimization problem similar to the BLISS approach. However, the main difference is that the top-level is not an automated optimization but an interactive process. The architect creates the first drawings on a blank paper and respectively simple models in the computer. Then in a dialogue, these models are changed due to performance or other feedbacks from clients or expert engineers. In the presented approach, the architect creates the initial design in a CAD program and then can adjust it according to the feedback of the DSEAM. The result a design flow of optimization that is structured into two loops as described by Geyer (2009). The inner loop serves the DSE and provides the performance information. Given a computable model of the performance depending on the degrees of freedom (design variable and structure-changing variants), automated techniques of DSE can be applied.

Since not all objectives and constraints can be translated into computer understandable models, the evaluation of the design cannot be completely automated. Therefore, the outer loop consists in an interactive process developing the design. The architect evaluates the non-computable aspects and selects solutions of the broad range of computer-generated suggestions or develops the models further and starts a new round of the inner cycle. Therefore, all design variants are displayed within the CAD System and can be explored in a computer environment commonly known by architects.

4. CONSTRAINTS

Due to their character, constraints split into two categories. The first category is numeric and thus is well expressible by the mathematical form, as it is usual for optimization:

$$g(\mathbf{x}) \leq 0. \qquad (1)$$

The function g describes the numeric constraints to comply with depending on the design variables $\mathbf{x}$. For instance, such a constraint can implement a minimum distance between columns or the maximum investment cost of a project in the DSE by such a constraint. As these constraints are explicitly set up as formula, we call them explicit constraints. Furthermore, constraints can form a hard limit, such as a fixed financial budget not to be exceeded, or soft and discussable boundaries, such as the ratio of room depth and room height; in the latter case, an exceeding is awarded with a penalty. To implement this difference, several functions are available translating these constraints, in the first case, to barrier functions not to be exceeded or, in the second case, to penalty functions, which can be exceeded for certain costs, as discussed by Papalambros & Wilde (2000, Chapter 7.6).

The second category describes constraints that are non-numerical and exhibit a qualitative or structural character. The choice of elements and how they are linked, i.e., the structure of the model represents such constraints. As these constraints usually rely on tacit knowledge that is difficult to express as formula explicitly, we call them implicit constraints. For instance, selecting tubular structure integrating the stairs and the elevator to absorb the lateral loads instead of three shear walls results from tacit knowledge on the organization of floor plans and their flexibility. These implicit constraints are an important means to define the design case as optimization problem for DSE. They closely relate to the usual interactive way of modeling in building design, as the designer sets them interactively during the modeling process. Therefore, the transfer of the interactive modeling to the definition is of major importance as it is described in the following sections.

The information for design optimization has to be taken from the architects' graphically entered CAD model. It can be either available directly in the model, derived from the model data, like geometry data (areas, volumes, surface areas …) or determined as design intent (wall type from wall thickness or windows size from further definitions), and finally, automatically generated (Sanguinetti et al. 2012). To get as accurate as possible, this requires objects of modeling that include the necessary definitions (semantics) to define the constraints. Environments of Building Information Modelling (BIM), such as Autodesk Revit (2012) partly provide the necessary semantically rich objects. However, the extension by objects specific for the definition of optimization problems is required to describe the design with its limiting requirements and its design space for DSE.

4.1 Objects to interactively define constraints

According to the concept of implicit constraints, one important element are appropriate elements to define the functional or aesthetic constraints of the design case in such a way that the essential requirements and characteristics are captured but the latitude for DSE is available. This section proposes some modified elements for interactive CAD environments.

4.1.1 Conceptual Volumes

Within the CAD environment, the architect can work with two different types of conceptual volumes, which represent the recent evolution of the design within the design process. In the very beginning, the architect thinks about how to fit the building's volume in the environment and that it must not exceed the local restrictions like plot boundaries and maximal building heights (Figure 1). In this stage the blocks represent the outer shell of the building. Also setback storeys on top of the building can be modelled.

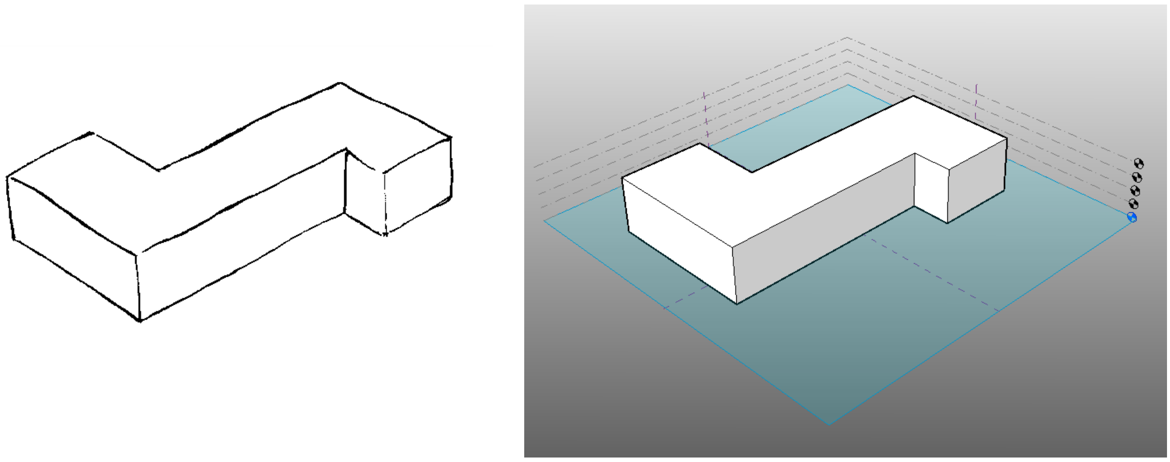


Fig. 1: Conceptual Volume as hand drawing (left) and as a 3D-modell in a CAD tool (right).

If a satisfying arrangement is found, the architect can divide the blocks into sub-volumes which represent the usage areas of the building like office spaces, horizontal and vertical access areas, entrance area, social spaces etc. Forces are added accordingly to the use of the area. Furthermore, the different storey can be defined by global horizontal levels (Figure 2). In this stage of the design, the arrangement of the rooms is not taken into consideration. The finest resolution of the spaces is the usage areas.

4.1.2 Façade

For the façade-system itself only basic parameters are adjustable. After the architect has defined a façade system (like full/structural glazing or punctual façades), the range of percentage of glassing is defined by the selected system itself (design intent). For the glass itself, the overall heat transfer coefficient (U-factor), the Visible Transmittance (VT) and the costs can be chosen in steps from low to high in the properties of the façade. With this information structure, the architect doesn't need to think about the exact values in this early design stage. The constraints are generated automatically according to the basic definitions.

Furthermore, it allows the tool to choose from a higher amount of options that are stored in an internal database and can be updated without affecting the appearance of the tool itself. For the opaque parts of the facades the U-value and the costs can be defined in the same way as described above.

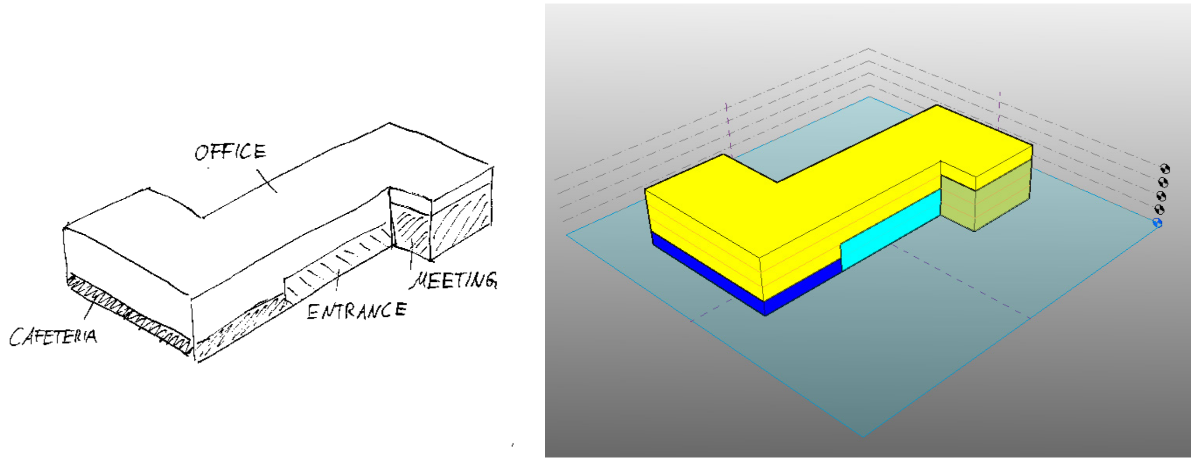


Fig. 2: Conceptual mass divided in the different usage areas entrance, meeting, office and cafeteria spaces in a conceptual sketch (left) and as masses in a CAD tool (right).

4.1.3 Structure

To generate the structural work automatically further information is required. The number of floors, defined by horizontal levels, and the dimensions of the building are given by the input of the architect and therefore can be derived from the model. The vertical loads can be determined as design intent according to the usage areas.

5. OBJECTIVES

To assess a proposed respectively generated design solution, it is required to apply a scheme of evaluation criteria. These criteria form the basis for the objectives; the objectives aggregate one or more criteria, e.g., by the weighted-sum method as it is practiced by the DGNB system. By allowing more than one aggregation the definition can form a multi-criteria problem, for instance, according to the major categories of sustainability ecologic quality, economic quality, and sociocultural and functional quality; also the addition of individual objectives according to the wishes of the client, designers etc. is possible, which is not discussed here.

As our approach focuses on sustainability and its computer support, this section examines indicators given by the DGNB certification system as criteria for the use with the DSEAM. Considering the automated DSE, the objectives split up into three categories:

(1) On the one hand, there are criteria that the search method can evaluate automatically without any intervention of the designer; an example are the environmental impacts of materials (e.g. emission of gases being harmful to climate) in case the BIM-based model includes all material definitions and a comprehensive data base is available.

(2) On the other hand, for a part of the criteria, no automated evaluation is possible and an expert assessment is required. For instance, the flexibility and the effort for, e.g., changing the building technology are especially in early phases only assessable by an expert. The strategy in this case is to define the desired level of flexibility and to include this definition as implicit constraints, such as a configuration of vertical shafts, or as explicit constraints, such a minimum height for ceiling installations, in the DSEAM.

(3) A third category includes criteria that need only some interventions. They require a combination of measures for implementation in the DSEAM. Construction costs are an example. The quantity determination is already automated very well. However, the estimation of the specific costs of one kind of construction in a specific situation requires the experts' experience.

The following sections discuss the indicators of sustainability and its use as objectives in the DSEAM in detail. The objectives for the automation are taken from the German DGNB (Lemaitre and Deutsche Gesellschaft für Nachhaltiges Bauen 2012). But since the early design stage of a building addresses not all of the DGNB criteria, the relevant objectives are named.

5.1 Eco-balancing – emission induced environmental impacts (ENV1.1)

The criterion "ENV1.1 Eco-balancing – emission induced environmental impacts" of the DGNB uses the following environmental impacts:

- Global Warming Potential (GWP) in kg CO_2-equivalent

- Ozone Depletion Potential (ODP) in kg R11-equivalent
- Photochemical Ozone Creation Potential (POCP) in kg C_2H_4-equivalent
- Acid Potential (AP) in kg SO_2-equivalent
- Eutrophication Potential (EP) in kg PO_4-equivalent

The components that have to be considered are listed according to DIN 276, which requires modelling representing building parts such as walls, columns, slabs etc. As these elements are not completely included in the early design phase, further assumptions and approximations are required. Furthermore, transport and site products and installation processes are not included in the DGNB objectives that would be hard to provide at this stage of the development of the building.

In the use phase, the energy consumption of the building is calculated on the basis of the German EnEV (2009), and DIN V 18599 (2011). Therefore, many tools already exist that can be included for an overall calculation of energy consumption for the different usage areas defined by the architect. But these tools often lack the need for exchange formats to run the calculation without generating a specified model from scratch.

Furthermore, the costs and energy consumption for maintenance and replacement of building components and the materials it consists of is stipulated by DGNB. This is mainly not calculable because exact knowledge of the use of the building, the arrangement of rooms or inner walls and technical installations is required, which cannot be delivered in the conceptual phase.

To calculate the impact on eco-balancing at the end of the building life cycle, following materials have to be distinguished: metals, mineral materials, materials for thermal use, materials that need to be deposited and mechanical systems.

5.2 Eco-Balancing – Primary Energy (ENV2.1)

The primary energy consumption for building operation is calculated on the basis of the German EnEV (2009), which is possible automatically to a high degree (Schlueter and Thesseling 2009). The system boundary has to be defined consistent and the period under consideration is fixed to 50 years.

The calculation is based on:

- The components (All used materials for structure and mechanical systems)
- The related processes.
- Energy consumption during the use of the building. The energy for the user specific equipment is not taken into consideration.

To calculate the impact on eco-balancing in the end of the building life cycle, the materials have to be distinguished as in ENV1.1 (see above).

The data has to be taken from the Ökobau.dat (2012) or the EPDs (2012). If the data is taken from somewhere else it has to be punished with an addition of 10%. It is based on a reference building method.

5.3 Use of Space (ENV2.3)

The criteria of space usage for the building are calculated on the basis of the use before it has been built. It rewards the reuse of industrial or polluted areas and punishes use of green areas. In this particular case the ecological compensation area is always calculated like unpolluted open space is used.

5.4 Building life-cycle costs (ECO1.1)

Costs are normally included as explicit constraint, either with or without a penalty function. In the presented approach, the costs are considered as objectives and therefore are not restricting the solutions if the desired amount is exceeded. This is necessary, because in some cases it might be suitable to exceed the costs slightly to achieve a better design.

Furthermore, costs are included not only for the construction, but as well for usage, maintenance and demolition of the building. The later retrofitting of the new building is considered as well, since it influences costs when the use of the building has to be changed (costs for construction, time when building cannot be used etc.) as well as on the sustainability, because of the materials that are exchanged during retrofitting.

The costs are estimated using the Present Value Method in the simplified procedure presented in the DGNB (Lemaitre and Deutsche Gesellschaft für Nachhaltiges Bauen 2012), including structural systems, HVAC-systems, supply and disposal costs, costs for cleaning and caretaking and costs for service and maintenance of the building.

5.5 Flexibility (ECO2.1)

For the definition of the flexibility the existing criteria are: the area efficiency factor, the storey height and the building depth. Furthermore, the categories for the use of space within the building can be evaluated like vertical escape routes per storey, number of sanitary installations, structure should use non-bearing inner walls and the structure itself should be oversized and HVAC-systems should be exchangeable easily.

5.6 Thermal Comfort (SOC1.1)

The thermal comfort has to be proofed for both the heating and cooling period. However, additional information on the use and design of the façade and the building equipment is required, which is often not available in early design phases. Typical indicators are the operative temperature, draught, relative temperature asymmetry and floor temperature, and relative humidity.

5.7 Analysis of criteria

The criteria described above are relevant ones for conceptual design. Finally, the criteria have to be evaluated, if they can be analysed automatically or require user intervention and which prerequisites have to be given. The classification is given in Table 1. Since most of the criteria are in category (3), it can be seen that for finding the best performing solution a strong interaction with the user is required.

Table 1: Categories of the different criteria

Criteria	Category	Prerequisites
ENV1.1: Eco-balancing – emission induced environmental impacts	(1) Automatic	model contains all information for the materials; connection to a comprehensive database; HVAC system for use phase.
ENV2.1: Eco-Balancing – Primary Energy	(3) Semi-Automatic	model contains all information about materials; connection to comprehensive database; User interaction needed for: energy consumption in using the building; processes related to construction.
ENV2.3: Use of Space	(3) Semi-Automatic	ecological compensation space on the basis of former unused space; further specification needs user's knowledge.
ECO1.1: Building life-cycle costs	(3) Semi-Automatic	model contains all information about material costs; user needs to asses specific costs; cleaning calculated per squaremeter; service and maintenance costs
ECO2.1: Flexibility	(3) Semi-Automatic	Area efficiency factor, storey heights and building depths can be checked automatically; all other values need user input.
SOC1.1: Thermal Comfort	(1) Automatic	model containing all information about materials and HVAC systems used.

6. GENERATION OF WELL PERFORMING SOLUTIONS

After the architect has defined the first idea using the above described elements, the DSEAM will perform the automatic generation and search of solutions. It consists of an outer and several inner loops. The architect is working in the outer loop, the inner loops serve for different subordinate optimizations: geometric, energetic, structural/topologic, costs, etc. These are the dimensions of the Design Space that the architect can explore in the outer loop.

The DSEAM modifies the geometry within the boundaries defined by the architect, e.g., the building can be moved on site, get shorter but higher or lower and wider. The orientation is not modified because in most cases it is fixed due to external restrictions (like other buildings or infrastructure) where the entrance areas, offices and other usage areas are aligned to. Furthermore, there is no optimization of floor plans included in the manner of the new arrangement of rooms. The usage areas are used to calculate the minimal floor height needed for the use, if the required daylight-factor is achieved and if the evacuation routes do not exceed the required length.

The HVAC components can be defined for a usage area for the whole building from predefined regular systems. The computation in this stage consists of e.g. the heating/cooling power needed for whole building, calculation of solar loads, area/volume ratio, and façade area. Further simplified models of comfort will be included that do not use simulation due to modeling effort and quick response.

Modifications by the DSEAM here are e.g. a rearrangement of the usage area within a certain field and an adjustment of the storey heights to find an optimal solution for the structure of the building and fulfil all constraints from local laws like minimal room heights according to the use and maximum escape route lengths. The material of the structure is automatically generated and modified by the DSEAM. At this stage the material is not fixed due to find the optimal use of resources for the structure.

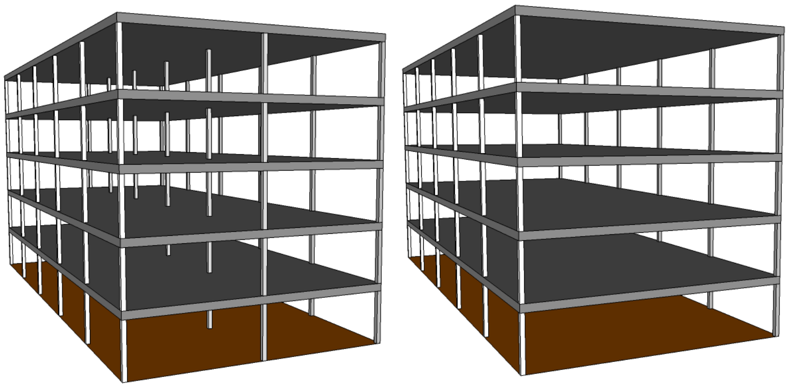


Fig. 3: Before the generation and calculation the architect can define if columns should be used within certain spaces. The columns would then be placed (left) or not (right) affecting other structural elements like slabs and the columns in the outer rows.

The areas for the structure are computed according the conceptual volumes for the different usage areas and additional information, such as if it is possible to place columns in an area or a column free space is required (Figure 3).

Costs for the materials, processes and energy use is summarized. With this, the architect is enabled to understand the influences of decisions for the whole building life cycle.

The well performing solutions are then selected by the DSEAM and then displayed as in Figure 4. The architect can explore the different solutions and select and if necessary modify the preferred solutions. After every modification the automatic search can be started again, until a satisfying solution is found.

7. CONCLUSIONS

In the early design stages, architects have to cope with a huge design space that cannot be explored manually without a great experience by the architect. But this is necessary because of its high impact on the later performance of the building. The Design Space Exploration Assistance Method (DSEAM) is a new approach, which enables architects to explore the design space more easily. It combines an automated search for well performing solutions with the non-computable tacit knowledge of the architect in an interactive process.

Therefore the different objectives that are important in the early design stages are named in this paper and split in three categories; (1) automatic, (2) non-automatic and (3) semi-automatic i.e. only some user interaction is required.

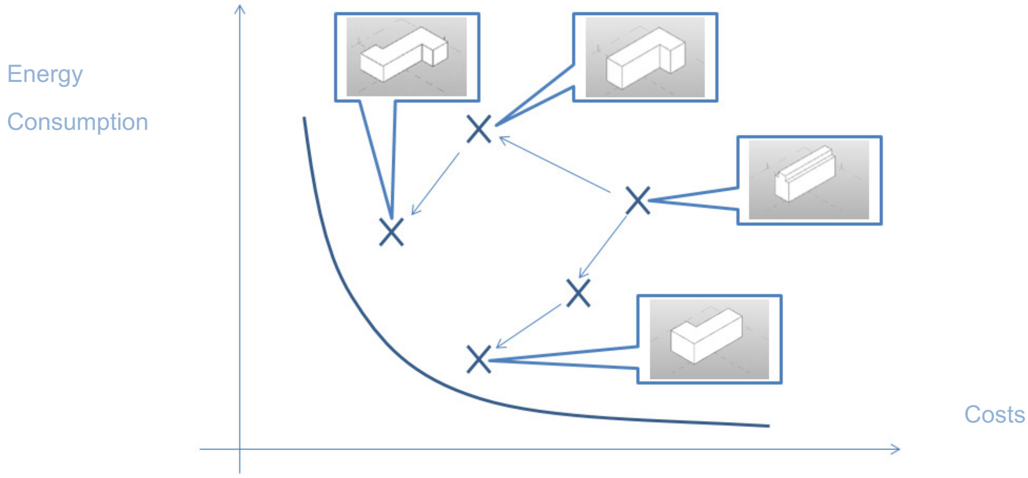


Fig. 4: After the automatic generation and search for well performing solutions, the architect can explore the different variants manually (here for a two-dimensional design space).

For the non-automatic part, the DSEAM is implemented in a CAD tool, to integrate the new approach in an interactive modelling environment common to most architects. Though they do not have to switch their kind of working to use the DSEAM. The automated part of the DSEAM consists of different analysis, namely (1) geometric (2) energetic (3) structural/topologic and (4) costs and methods of DSE, for which in this paper optimization was chosen. The analysis is relying on the definitions of the DGNB (Lemaitre C. and Deutsche Gesellschaft für Nachhaltiges Bauen 2012) to enable sustainable design from the very beginning of the planning process.

There are two major limitations in this process. On the one hand, that the databases for the building materials in terms of sustainability are not complete i.e. many materials are missing or cannot be calculated yet which has influences on the number of solutions calculated and may exclude better ones. On the other hand, there are some deficits in calculation since due to calculation speed not all parts can be included (like welding work or screw for connecting bearing parts) which will reduce accuracy compared to the outputs of the final design.

Further steps of the development are elements for interactive modeling, the design process and the graphical interface for the exploration of the solutions including the visualization of the different solutions of the inner cycle. Furthermore, an export format has to be developed that enables the further use of the generated information.

8. REFERENCES

Autodesk Revit (2013). Revit 2014, *Autodesk, Inc.*. Available at: http://usa.autodesk.com/revit/.

Autodesk Green Building Studio (2013). Green Building Studio, *Autodesk, Inc.*. Available at: http://www.greenbuildingstudio.com.

BREEAM (2008). BRE Environmental Assessment Method, *Building Research Establishment (BRE)*. UK. Available at: http:www.breeam.org

DIN V 18599 (2011) Energetische Bewertung von Gebäuden, Bundesamt für Bauwesen und Raumordnung (BBR)

EnEV (2009). Verordnung über energiesparenden Wärmeschutz und energiesparende Anlagentechnik bei Gebäuden (Energieeinsparverordnung – EnEV 2009). Available at: http://www.enev-online.de/.

EPD (2012). Environmental Product Declaration, *Institut Bauen und Umwelt e.V. (IBU)*. Germany. Available at: http://bau-umwelt.de/hp474/Umwelt-Produktdeklarationen-EPD.htm.

Fernandez-Ceniceros, J., Fernandez-Martinez, R., Fraile-Garcia, E. and Martinez-de-Pison, F.J. (in press). Decisions support model for one-way floor slab design: A sustainable approach, *Automation in Construction*, Vol. 0, No. 0. Available at: http://www.sciencedirect.com/science/article/pii/S092658051300099X.Gane V. and Haymaker J. (2012). Design Scenarios: Enabling transparent parametric design spaces, *Advanced Engineering Informatics*, Vol. 26, No. 3, 618–640. Available at: http://www.sciencedirect.com/science/article/pii/S147403461200047X.

Gerber D.J., Lin S., Pan B. and Solmaz A.S. (2012). Design optioneering: multi-disciplinary design optimization through parameterization, domain integration and automation of a genetic algorithm, *Proceedings of the 2012 Symposium on Simulation for Architecture and Urban Design,* Society for Computer Simulation International, San Diego, CA, USA, 11:1-11:8. Available at: http://dl.acm.org/citation.cfm?id=2339453.2339464.

Geyer P. (2009). Component-oriented Decomposition for Multidisciplinary Design Optimization in Building Design, *Advanced Engineering Informatics.* Vol. 23, No. 1, 12-31. Available at: dx.doi.org/doi:10.1016/j.aei.2008.06.008.

Granadeiro V., Duarte J.P., Correia J.R. and Leal V.M. (2013): Building envelope shape design in early stages of the design process: Integrating architectural design systems and energy simulation, *Automation in Construction*, Vol. 32, No. 0, 196–209. Available at: http://www.sciencedirect.com/science/article/pii/S0926580512002415.

LEED (2009). Leadership in Energy and Environmental Design, U.S. Green Building Council. Version 3. Available at: http://www.usgbc.org/leed.

Lemaitre C. and Deutsche Gesellschaft für Nachhaltiges Bauen (2012). *Neubau Büro- und Verwaltungsgebäude: DGNB Handbuch für nachhaltiges Bauen; Version 2012,* Deutsche Gesellschaft für Nachhaltiges Bauen. Available at: http://books.google.de/books?id=1kdOMwEACAAJ.

Mahsuli M. and Haukaas T. (2013) Computer Program for Multimodel Reliability and Optimization Analysis, *Journal of Computing in Civil Engineering*, Vol. 27, No. 1, 87–98.

Mensinger M., Huang L., Zhang P. and Hogger H. (2012). Optimization of sustainable office buildings in steel using genetic algorithms, *Proceedings of the Nordic Steel Construction Conference 2012*, Oslo, Norway.

Microsoft Excel (2013). Excel, *Microsoft Corporation*. Available at: http://office.microsoft.com/en-us/excel/.

Ökobau.dat (2012). Ökobau.dat 2011 v5, *Bundesministerium für Verkehr, Bau und Stadtentwicklung.* Germany. Available at: http://www.nachhaltigesbauen.de/oekobaudat/index.php.

Papalambros P.Y. and Wilde D.J. (2000). *Principles of Optimal Design: Modeling and Computation,* Cambridge University Press, New York, NY, USA.

Sanguinetti P., Abdelmohsen S., Lee J., Lee J., Sheward H. and Eastman C. (2012) General system architecture for BIM: An integrated approach for design and analysis, *Advanced Engineering Informatics*, Vol. 26, No. 2, 317–333. Available at: http://dx.doi.org/10.1016/j.aei.2011.12.001.

Schlueter A. and Thesseling F. (2009). Building information model based energy/exergy performance assessment in early design stages, *Automation in Construction*, Vol. 18, No. 2, 153–163. Available from: http://www.sciencedirect.com/science/article/pii/S0926580508001064.

Shi X. and Yang, W. (2013). Performance-driven architectural design and optimization technique from a perspective of architects, *Automation in Construction*, Available at: http://www.sciencedirect.com/science/article/pii/S0926580513000253.

Sobieszczanski-Sobieski J., Agte J.S. and Sandusky R.R. (1998). Bi-Level Integrated System Synthesis (BLISS), *NASA Langley Technical Report Server.* Available at: http://arc.aiaa.org/doi/pdf/10.2514/6.1998-4916.

Wu W. and Issa R. R. A. (2012). Leveraging Cloud-BIM for LEED Automation, *ITcon*, Vol. 17, 367-384. Available at: http://www.itcon.org/2012/24.

OFFLINE SPATIAL PANORAMIC VIDEO AUGMENTATION FOR VISUAL COMMUNICATION IN THE AEC INDUSTRY

Stéphane Côté
Bentley Systems, Québec, Canada

Julien Barnard
Dept. of computer science, Université Laval, Québec, Canada

Rob Snyder
Bentley Systems, Lexington, KY, USA

Renaud Gervais[2]
Bentley Systems, Québec, Canada

ABSTRACT: *Renovation of existing buildings is a type of construction work that requires a very good understanding of the existing built environment. Accurate bidding and proper planning for such construction projects requires detailed information both from the 3D CAD model and of the existing building. The problem is both sources of information are heterogeneous: one is in the form of digital data (2D CAD drawings, 3D CAD models), while the other is the actual physical world. The CAD model and drawings deliver the designer's construction intent, while the physical world provides integration context. A user must do significant mental efforts to merge the 2 types of data and form a mental image of the work that is actually required. In this paper, we present a technique that enables the visualization of augmented scenes, packaged in a visualization application that can be used on site or off site by construction bidders, planners and workers. The building environment is first captured by walking in the area holding a panoramic video camera. The panoramic video stream is then post-processed to align each of its frames with a 3D model of the building. A user can then use the viewer to navigate the pre-recorded photo-realistic scene at any location and orientation along the camera paths, and augment it with the 3D model, to reveal hidden structure represented in the model, or 3D elements showing future portions to be added. Our method was tested on a building for which a detailed 3D CAD model (BIM) was available. Results show that the system could enable a better communication between the designer and the builder by displaying the designed construction intent in its real context, and therefore could allow more accurate bidding and work planning, and generally, could facilitate better understanding of the work to be done.*

KEYWORDS: *Augmented Reality, environment, panorama, CAD model, BIM, construction, renovation.*

1. INTRODUCTION

Renovations and additions to existing buildings are types of work that are constrained by existing structures. For new structures to fit well with the existing environment, the CAD model needs to be designed with care and detailed knowledge of the existing building. Similarly, for accurate bidding and proper planning of such construction projects, detailed knowledge and understanding of both the CAD model and the existing building is required.

One source of difficulty that might arise is that both sources of information are heterogeneous: one is in the form of digital data (2D CAD drawings, 3D CAD models), while the other is the actual physical world. The CAD model and drawings deliver the designer's construction intent, while the physical world provides integration context. User interpretation involves the effort to merge the 2 types of data and form a mental image of the work required. The problem is one of communication: we need to present the real world and model data together in such a way that the work to be done can be visually understood.

Augmented reality could provide an interesting solution to that communication problem by allowing real time navigation and interaction in an information environment that combines the physical world and the CAD data: a user would walk around, or in, the building, raise a handheld device, and see the surrounding scene augmented with aspects of the 3D model relevant to the planned work. Such an application would enable the visualization of the augmented environment from any location and would facilitate the understanding of the relations between the

---

Citation: Côté, S., Barnard, J., Snyder, R. & Gervais, R. (2013). Offline spatial panoramic video augmentation for visual communication in the AEC industry. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

[2] Current affiliation : INRIA, Bordeaux, France.

physical world and the proposed designed world. However, to be of any use, the augmentations would need to be very accurate. Indeed, decisions taken by architects, engineers and construction workers have a direct impact on public safety. Those must therefore be supported by accurate data. Although approximate, low accuracy augmented reality is easy to achieve, live accurate augmentation is still a challenge. In addition, augmented reality would not solve all problems:

- Augmented reality is used to augment the live environment. That means users have to be physically located on site in order to see that site in an augmented fashion. They actually need to be located at the exact position from which they want to see the world augmented. Although that makes sense and can probably be achieved easily for typical city environments, it may not always be ideal for engineering / construction applications. For instance, problems may arise when a user wants to augment the building from a location where it is unsafe or impossible to stand (ex: nuclear reactor, high voltage area, etc.).
- Remote workers who may want to view the site in an augmented fashion will only be able to do so if they travel to the site and augment it in person. They could remotely view a live augmented session done by a colleague located on site – but that requires someone there to assist them when they need it, and they still need to give them navigation instructions that could be complex to explain verbally on the phone.
- Other users might also want to review an augmentation session they did in the past, to check a measurement for instance, something that live AR cannot provide.
- Sometimes they might want to check some augmentation carefully, without having to hold a handheld device in their hands, in the direction of the augmented area.
- Live augmentation requires the tracking of the position and orientation of the hand held device, something that is hard to achieve precisely and accurately in real time. Pre-recorded environments avoid that problem by post-processing all frames after capture, leaving time to accurately align the model with each frame of the video, ensuring stable and accurate augmentations regardless of users' movements.
- Also, while construction communications are being developed by the design team, pre-recorded photographic environments may indeed become a very important aspect of a combined information environment within which designers author their instructions, anticipating that those communications will be viewed later, onsite, immersively, to help people understand the work they are doing. In this sense, offline pre-recorded video may become an essential part of the information environment within which designers and builders author communications, receive them, and interpret and discuss them.

In many cases, and for the reasons stated above, such pre-recorded environments may become preferable to augmented reality. For both authoring and viewing, what would be needed is an augmentation technique that enables users to view the augmented environment remotely without needing assistance from anyone on site, without being constrained to navigating only on physically walkable areas, while being sufficiently immersive to give them the illusion that they are physically on site.

In this paper, we present a technique that enables the augmentation of pre-recorded scenes, packaged in a visualization application that can be used on site or off site by designers, construction bidders, planners and workers. The building environment is first captured using a panoramic video camera that is moved along a path in the area to be augmented. The video stream is then post-processed to align each of its frames with a 3D model of the building. This alignment makes the augmentation possible: a user can then use the viewer to navigate the pre-recorded photo-realistic scene at any location and orientation along the camera paths, and augment it with the 3D model. Further, the combined environment then can be transformed in ways that support specific, clear communication. Our method was tested on a building for which a detailed 3D CAD model (BIM) was available. Results show that the system enables a better communication between the designer and the builder by displaying the 3D design in its real context, and therefore would allow simpler, less expensive and more accurate bidding and work planning, and generally allows better understanding of work that is to be done, which may improve the efficiency, and correctness of performed work.

Our main contribution is a system for the capture and visualization of panoramic video environments that overcomes several of the limitations of augmented reality in the construction context, whilst providing an AR-like experience.

2. RELATED WORK

Over the past few years, the potential of using panoramic imagery for augmenting scenes has been studied (Côté 2011a, 2011b, 2012; Wither et al., 2011). Langlotz et al (2012) demonstrated live augmentation of pre-recorded video from a fixed position. Hill et al (2011) showed a mirror world augmentation system in which pre-captured panoramic images of the environment were augmented when the user stood at approximately their capture position. Static images offer the advantage of providing precise augmentation (since no camera tracking is required). Augmentation based on panoramic media also has the potential of being much more accurate because of the numerous points of control located all around the camera that can be tracked over long distances (Lemaire and Lacroix, 2007) and increase the chance of capturing areas of the environment that are suitable for tracking (Wither et al., 2011).

While being frozen in time, augmentation based on static images has been used extensively for advertising (ex: Zhu et al., 2004). In such applications, augmentation is achieved on a paper marker, resulting in an augmentation that is often disconnected from the physical reality around the user. Yet, those applications are popular and serve their purpose. Such offline augmentation could very well find applications in the AEC world too, as it offers the advantage of providing users with the benefits of on-location augmented reality, while also providing access to real-world information not normally available when remote (Mankoff et al. 1998).

The use of augmented reality in the engineering world has also been investigated by several teams. For instance, Woodward et al. (2010) present a mobile AR system for viewing BIM data on construction sites. Schall et al. (2010) describe a technique for visualizing underground infrastructure using AR, and Su et al (2013) looked at the uncertainty related with such visualization. Georgel et al. (2007) proposed a technique for industrial discrepancy check using augmented reality. The vast majority of the works related with augmented reality in the engineering world investigate live augmentation, tracking quality being the most common concern. In this work, we chose to augment static imagery, to the benefit of augmentation precision, accuracy, and offline visualization.

3. METHOD

3.1 Data

Our method is based on the augmentation of pre-recorded panoramic video streams captured along a path in the area to be augmented. Panoramic streams are captured using a Ladybug panoramic video camera from Point Grey Research. For outdoor scenes, the camera is installed on top of a tripod and carried by a user who also carries a laptop using a shoulder laptop holder. For indoor scenes, the tripod is installed on a dolly onto which the laptop is also installed, and that is moved inside the building. The laptop runs a program developed in-house using the Ladybug SDK that basically captures the individual video streams obtained from the 6 individual cameras sensors, merges them into one single equirectangular panoramic video stream, and stores them on disk in real time as 6 faces of a cube.

Panoramas are augmented using a detailed 3D CAD model that was imported in our augmentation program. In addition to the usual elements (walls, floor, etc.), the model also contains numerous elements representing hidden objects like structure, pipes, etc. The augmentation is used to render those objects that are normally invisible in the physical world because of wall surfaces.

3.2 Publication process

The first step in the augmentation process is to align the CAD model to the panorama. This is done manually using the technique described in (Poirier, 2011): the pre-recorded panorama stream is loaded by the program, its first frame displayed on screen. The CAD model is then overlaid on top of it. Through a manual user interface, the user selects a set of control points on the model, and the corresponding locations of those points in the panoramic image. The camera pose is then calculated using a panoramic pose calculation algorithm, as described by Poirier. Since each frame of the video needs to be aligned with the model, we use a panoramic image tracking algorithm described in (Côté et al, 2013): features are identified in the first image and their 3D position is estimated by projection onto model faces from the camera position. These features are then matched with those in the second frame. Their 3D position is inferred from that correspondence, and the new camera pose is calculated using the same panoramic pose estimation algorithm. This process is repeated for each frame, resulting in a stream of camera poses. In other words, the process results in the calculation of the camera position for each individual frame of the panoramic stream. Drift in the tracking process can occur, but its extent is minimized through the use of key frames. Remaining drift manifests itself by a misalignment between the model and the panoramic image. A new set of correspondence points between the model and the panorama is then used to fix the alignment and pursue tracking.

Once the alignment is complete, the set can be exported into an “augmentation package” that consists of an augmentation program, a set of panoramic streams, the camera pose for each frame of those streams, and an augmentation model.

3.3 Navigation and augmentation

The augmentation program included in the package basically consists of a panorama visualization tool: the first frame of the panorama stream is displayed on screen in a first person perspective (see Figure 1, left, top part) called the “augmented view”. A virtual camera is centered in that panorama, and renders it in the view. The user can rotate the view to look around and see the whole environment around the camera by dragging in the top view with a mouse pointer. Since the panorama stream is actually captured along a path, going to the next frame actually means moving the virtual camera to the next position along that path. This can be done by clicking on the virtual arrows displayed above the ground in the augmented view or on a dedicated key on the computer keyboard, which enables the user to move forward and backward along the camera path and see the environment from different vantage points.

To help the user orient himself in the virtual world, a map is also optionally displayed. The map is composed of the 3D building model, the camera path, and the current virtual camera position (see bottom part of Figure 1, left, and Figure 1, right). The user can change the position of the virtual camera by dragging its icon along the displayed path.

Fig. 1: Prototype view showing map, paths, camera position, translation arrows, and scene view (left). Model, seen from the top, showing 2 camera paths and virtual camera frustum (right).

In our current prototype, augmentation is achieved through a virtual excavation feature, that lets the user see through walls, floor and ceiling. The augmentation technique is similar to the one described by (Schall *et al.*, 2010; Côté, 2011b) for augmenting subsurface utilities. In these projects, a virtual excavation is drawn on the surface of the road, revealing hidden infrastructure (see Figure 2). The technique basically consists of creating a virtual hole in an object, by clipping all but some of the elements composing it. In this project, we used the same technique but applied it on walls, floors and ceilings.

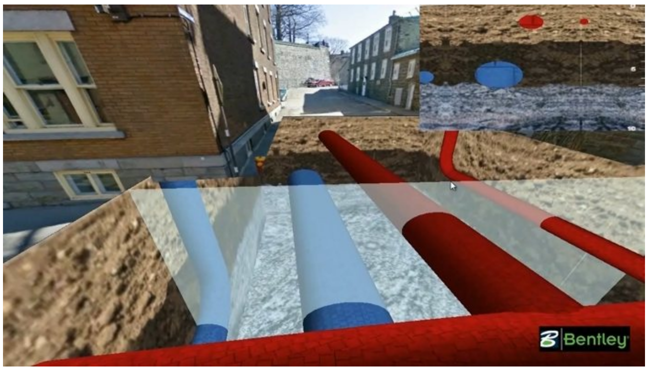


Fig. 2: Virtual excavation for subsurface utilities as shown in (Côté, 2011b).

4. RESULTS

We tested our method in the Paddy Wagon Irish Pub located in Richmond, KY, USA (Figure 3, left). We chose that site because we also had a detailed CAD model (BIM) of that building (Figure 3, right), created by *McKay Snyder Architects, James McKay, Architect*, using MicroStation® and had permission to use it given by the building owner. We captured 2 panoramic video streams, one inside the pub, the other one outside (see white paths in figure 1, right). Each individual panoramic frame was stored as 6 individual 1024 x 1024 pixel panels forming the sides of a cube. The augmentation package was then created, and the method tested.

The prototype user interface, shown in Figure 1 (left), enables the user to navigate in the environment while seeing his position on a 3D map. When panning the top view, the user actually rotates the virtual camera and can view the environment in all orientations. Clicking on the arrows displayed just above the ground moves the camera along the path. Zoom is also enabled. Manipulation on the bottom part of the view enables model rotation and zoom, as well as camera translation (by dragging the camera frustum icon along the paths).

Augmentation is achieved by right clicking on the top view and dragging to create a rectangle on the surface of a wall. When applied onto the outside walls of the building, it reveals the model interior (see Figure 4). Once the excavation is drawn, the camera can be moved along the path, revealing a different perspective both outside and inside the building. The excavation can also be moved along the wall, revealing other portions of the model.

Fig. 3: The Paddy Wagon Irish Pub (left) and its CAD model (right).

Although the excavation is a useful tool, it is often too drastic. If, for instance, one would be interested in viewing the network of pipes hidden inside the wall, a virtual excavation that clips all elements is useless, as it would also clip the pipes that one wants to view. The excavation object is actually a 3D volume attached to a 3D surface (the wall). Clipping away all the elements inside the excavation volume may be too much, as it cuts everything out. What would be desired is a way to select which elements are to be clipped by the excavation. We implemented a selective clipping tool and tested it on our dataset. In Figure 5, the left image shows the excavation applied onto an external wall, the one on the right shows the same excavation, but with 2 pipes (purple and red) not clipped by the excavation.

During our tests, we encountered several issues. For instance, when using the program, it became clear that the loading of sequential panoramic images when navigating along a path was too slow. Each image frame being 6 megapixels large, loading it and updating the display at a speed required by normal navigation in the building environment was slow and made navigation painful. We partly fixed that problem by keeping a buffer of panoramic frames into memory, and by storing a low resolution version of the panoramas. When the user keeps the traveling key or button down, the system simply loads the lower resolution versions of the panoramas and updates them, which produces a much smoother and faster movement. When he releases the key, the system automatically stops camera movement and loads the higher resolution version of the destination panoramic frame. That turned out to provide a much quicker navigation.

Another issue was related with the image frames' spatial density being higher than necessary: capturing 15 FPS while walking at a speed of about 3 km/h results in frames captured at camera positions only about 5 cm away from each other. For outdoor augmentation, such density is not really necessary, and results in an unnecessarily large augmentation package. Moreover, the spatial frame density varied along the path because the user carrying the camera cannot easily walk at constant speed. To fix that and provide a visualization path with more regularly spaced frames, we implemented a basic downsampling algorithm that automatically selects a subset of the frames that are equally distant based on a user-chosen target spatial density.

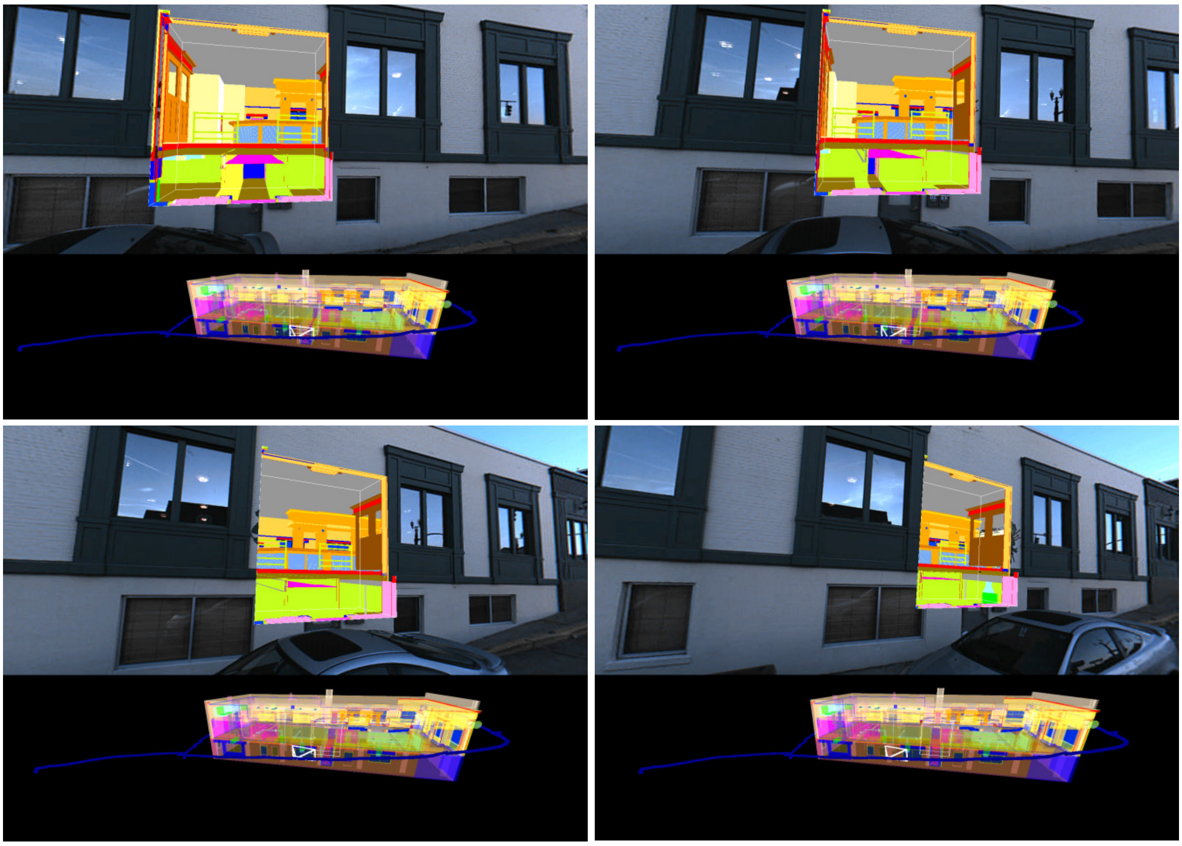


Fig. 4: Virtual excavation displayed on external building wall, as the camera is being moved from right to left.

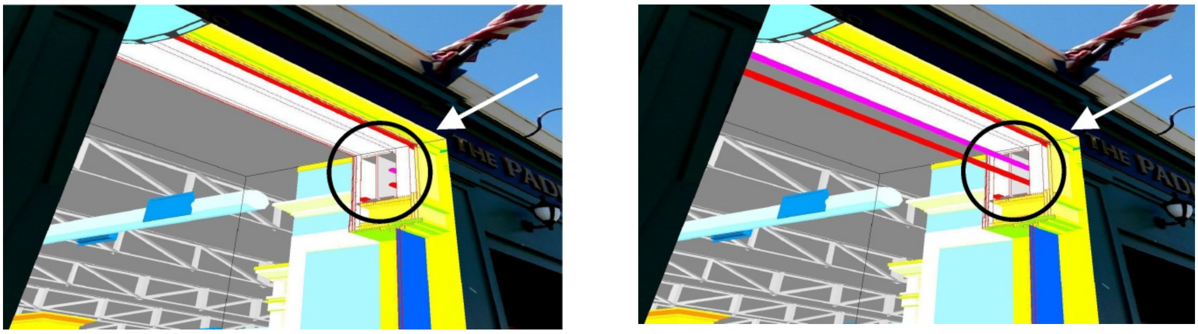


Fig. 5: Virtual excavation showing selective clipping applied on selected pipes.

The use of the system showed stable augmentations not characterized by the typical jittering observed in typical augmented reality systems. Augmentation was always stable, although some inter-frame jittering was observed, which was probably due to our tracking algorithm that was not sufficiently accurate. Once those tracking errors are removed, the resulting augmentation will be stable both temporally and spatially, and 100% deterministic.

5. DISCUSSION

Our experiment seems to confirm the potential of such tools for augmentation. The use of pre-recorded media allows prior accurate alignment between the model and the physical world, providing precise augmentation and potentially much more accurate than live augmentation techniques. Moreover, pre-recoded media allowed us to augment the site from a remote place, which could be very useful for planning site visits, or for doing a quick check on something one might have missed during the first visit, but without returning to the site. Finally, such augmentation of pre-recorded media contributes to the authoring of communications that deliver designed construction intent, communications within the information environment that show, explain, clarify, communicate and direct, with regard to work to be done. The use of panoramic video captured along a path ensures minimal navigation constraints in spite of the fact that the media is pre-recorded. In other words, the user benefits from the immersive aspects of live augmentation, in addition to all the advantages of offline augmentation.

Unfortunately, the system is not perfect. The use of pre-recorded media implies, by definition, that the media is out of date. That means any dynamic event cannot be reproduced in the augmentation. The tool would therefore need to be seen as a package for offline augmentation, and used accordingly. Of course, this is suitable for primary design construction intent communications, where as always, it is understood that the real world may deviate over time from the design communications (like drawings). Those deviations are typically detected and understood by people, and usually do not invalidate the construction intent communications.

We see this prototype as a first step to achieving better communication in AEC. The combination of model data with the physical world is in its infancy, and is likely to develop into a set of tools that will not only facilitate communication, but also will help the construction worker directly in his building tasks.

Several minor improvements could be made to the prototype. Those include:

- Increasing the panorama rendering speed, to improve the navigation experience.
- Integrating other augmentation techniques, such as clicking on objects to identify them and display maintenance history and other element data, displaying plan and section drawings, etc.
- Using the tool for onsite augmentation. The system could automatically track the user's position and display the closest panorama that was captured in the area. Although this would only simulate true augmented reality, the resulting augmentation would have the advantage of being very precise and much more accurate than current outdoor live AR solutions.
- Using the tool for collaborative remote augmentation, where users could augment the area from their respective position and add annotations on this augmented environment, all at the same time.
- Display the camera path in the augmentation window, giving the user a better sense of where he can navigate in the physical world (see Figure 6, left).
- When used outdoor, the camera was carried by a user walking around the building. Although care was taken to walk in a smooth fashion, the camera moved up and down in the process (see Figure 6, right). This movement manifests itself as an apparent "shaking" in the resulting stream, when navigating from frame to frame. We could evaluate downsampling methods to properly select frames that would minimize that movement.
- Another issue we encountered is the fact that the tracking module did not always succeed in finding the exact camera pose. That resulted in temporal misalignment that is very clear when moving the virtual camera during augmentation. Work should be put on a better panoramic tracking method.

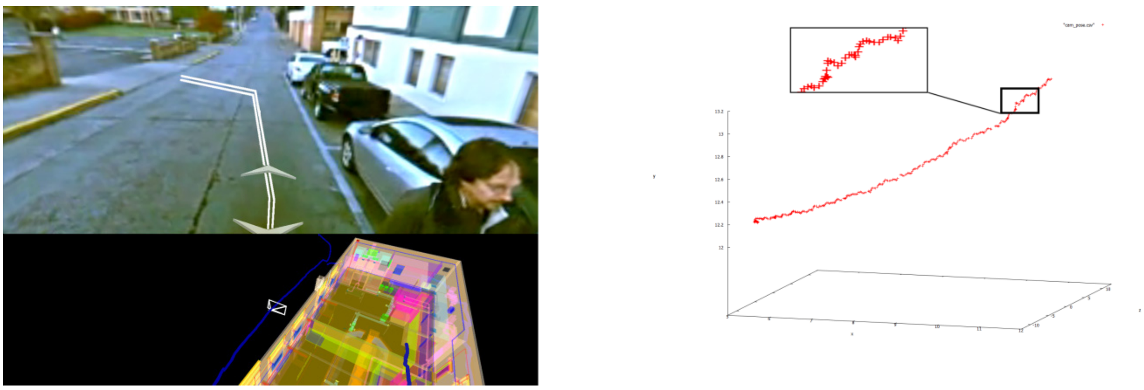


Fig. 6: Displaying the path in the panoramic view as a proposed improvement (left). Captured camera 3D positions that show user's movements while walking (right).

However, the method could also be pushed one major step further. In this experiment, we showed that an immersive pre-recorded environment that can be browsed freely using a virtual excavation and packaged in a viewer that can be used offline shares many of the benefits of true live AR. Although such a tool is likely to be useful to the AEC industry, it is interesting to note that the purpose of design authoring of communications is to show, explain, and clarify, to communicate directively, about specific work to be done. In that context, a browsing tool aimed at showing and revealing specific directive aspects and communications might be preferred. We envision that a directed browsing tool, showing users what to look at, understand, and do, would nicely complete the set of functionalities described in this paper, and would likely find more uses in the AEC world.

6. ACKNOWLEDGEMENTS

Many thanks to Mathieu Giguère and Marc-Antoine Desbiens for software development work, and to NSERC for financial support via the Industrial Undergraduate Student Research Award program.

7. REFERENCES

Côté S. (2011a). Augmented reality for infrastructure: a first step. Published electronically on *BE Communities*.

Côté S. (2011b). Augmented reality for underground infrastructure: the problem of spatial perception. Published electronically on *BE Communities*.

Côté S. (2012). Augmented reality for building construction and maintenance: augmenting with 2D drawings. Published electronically on *BE Communities*.

Côté S., Trudel P., Desbiens M., Giguère M., and Snyder R. (2013). Live mobile panoramic high accuracy augmented reality for engineering and construction. Proceedings of the Construction Applications of Virtual Reality (CONVR), London, England, Oct. 2013.

Georgel P., Schroeder P., Benhimane S., Hinterstoisser S., Appel M., Navab N., 2007. An Industrial Augmented Reality Solution For Discrepancy Check. Proceedings of the 6th International Symposium on Mixed and Augmented Reality (ISMAR), Nara, Japan, Nov. 2007

Hill A., Barba E., MacIntyre B., Gandy M., Davidson B. (2011). Mirror Worlds: Experimenting with Heterogeneous AR. 2011 International Symposium on Ubiquitous Virtual Reality, Jeju-si, Republic of Korea.

Lemaire T. and Lacroix S., (2007). SLAM with panoramic vision. *Journal of Field Robotics*, Vol 24.

Langlotz T, Zingerle M., Grasset R., Kaufmann H., Reitmayr G., 2012. AR Record&Replay: Situated Compositing of Video Content in Mobile Augmented Reality . OzCHI '12 Proceedings of the 24th Australian Computer-Human Interaction Conference.

Mankoff J., Somers J. and Abowd G.D., 1998. Bringing People and Places Together with Dual Augmentation, Proceedings of the Collaborative Virtual Environments conference CVE'98.

Poirier S. (2011). Estimation de pose omnidirectionnelle dans un contexte de réalité augmentée. M.Sc. Thesis, Université Laval, 2011.

Schall G., Junghanns S. and Schmalstieg D. (2010). VIDENTE - 3D Visualization of Underground Infrastructure using Handheld Augmented Reality, in GeoHydroinformatics: Integrating GIS and Water Engineering *(CRC press)*.

Su X., Talmaki S., Cai H., Kamat V.R. (2013). Uncertainty-aware visualization and proximity monitoring in urban excavation: a geospatial augmented reality approach. *Visualization in engineering*, Vol. 1.

Wither J., Tsai W-T., Azuma R., 2011. Indirect augmented reality. Computers & Graphics 35, 810–822.

Woodward, C., Hakkarainen, M., Korkalo, O., Kantonen, T., Aittala M., Rainio, K., Kähkönen, K., 2010. Mixed reality for mobile construction site visualization and communication. Proceedings of the Construction Applications of Virtual Reality (CONVR), Sendai, Japan, Nov. 2010.

Zhu W., Owen C.B., Li H., Lee J.-H. (2004). Personalized In-store E-Commerce with the PromoPad: an Augmented Reality Shopping Assistant. *Electronic Journal for E-commerce Tools and Applications*.

INTEGRATING SIMULATION AND VISUALISATION FOR ENERGY EFFICIENCY IN A LARGE PUBLIC MALL IN THE TROPICS

Puteri Shireen Jahnkassim
Department of architecture, International Islamic University Malaysia

Yousif Abakr
Environmental analysis and virtual reality group, International Islamic University Malaysia

Ihab Faisal Ibrahim
KAED, IIUM.

***ABSTRACT*:** *This paper reports on a case study that involved an integrated design process of a large commercial development. In particular, it utilized simulation and visualization to inform strategic design decisions that could reduce heat gain while admitting usable daylight. Additionally, the design intended to avoid extensive air conditioning energy of a large shopping mall in the tropical context of Malaysia. Simulation inputs were presented to a design team throughout the design process and on completion of the building, post occupancy studies were carried out to verify the results. At present, air conditioning is not used in large common public areas and hence, this case study represents a successful application of simulation and visualization tools of such context. The airflow and monitored temperature results verified the simulation output; however, the daylight measurement recorded higher distribution compared to the predicted performance. This may be due to the standard use of 10 k Cie overcast sky in simulation to represent the worst cloudy scenario in Malaysia. Regardless, the results will benefit future planners and developers of large shopping malls by recommending the integrated design process. This process introduces the usage of strategic passive design approach that can save a large amount of energy used in common areas.*

KEYWORDS: *multivolume, atria, canopy, thermal comfort, bioclimatic and ventilation*

1. INTRODUCTION

Large shopping centers are prominent features in developing cities. In tropical countries like Malaysia, these buildings are totally air conditioned and thus, require passive design strategies in order to lessen their lifelong operational costs incurring from active cooling. This research aims to adopt state of the art building simulation and visualization in the designing, building and monitoring of thermal comfort performance of a largely covered 70,000 square meter plaza or atria. In particular, it intends to promote passive design strategies by optimizing roof design that can limit solar gain and allow in daylight. This in turn, will offset trapped heat in a covered space.

Conducted as a case study, this research represents an ecological approach where a developer employs simulation expertise to assist in strategic design decision making for the purpose of reducing energy usage in the tropics. In particular, it aims to:

1. Identify the causes of heat gain, and
2. Determine predict and monitor both daylight and thermal comfort performance within the proposed space.

In tropical urban design, there is a growing trend of building residential suburbs on plaza outdoors (Hung & Chow, 2001 and Sharples & Lash, 2007). This feature acts like an external atrium or a courtyard, which often serves as a commercial and social hub in new urban developments. Constructed as an opened, semi-opened or covered space, the spacious courtyard often houses commercial activities like outdoor bazaars and food-courts.

Large urban spaces become prominent in tropical countries for several reasons. First, they serve to reduce isolation of city dwellers. Often included with this feature are glazed canopies that admit more variable and dynamic daylight and hence, produce a bright and cheerful atmosphere that can enhance marketing of goods and services. Following increased significance, developers begin to include such spaces as part of their marketing efforts.

Citation: Jahnkassim, P. S., Abakr, Y. & Ibrahim, I. F. (2013). Integrating simulation and visualisation for energy efficiency in a large public mall in the tropics. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

In view of the increasing importance of common spaces in large commercial buildings, it is imperative to ensure that these spaces do not consume a lifetime of high energy. For instance, a covered space may be typically designed with daylight admission and natural ventilation, which create a sort of enhanced semi-outdoor large atrium-like space. Equally important is to note that the roof of a large building (like shopping centers) in equatorial climate can represent the largest source of heat gain, particularly through radiation and conduction.

Some innovations in countries of temperate climate do not apply in their equatorial counterparts. For example, glass-covered atriums in those countries may introduce roof heat radiation and conduction when set up in tropical countries. Henceforth, more in-depth understanding is required to serve as parameters for tropical urban design, where thermal comfort in outdoor urban areas is more extended and varied than that of indoor climate.

2. METHODOLOGY

Through schematic and design development processes, a series of options were tested in order to optimize an innovative roof design to offset trapped heat in a covered space. The use of simulation tools was introduced at the very schematic design stage. Based on an existing design, the team worked closely with an architect to propose and test several options in line with aesthetic preferences. When options were shortlisted, the team further studied the performance of optional roof profiles in terms of daylight, glare and wind. These options were then, induced with cross ventilation results.

Results from the above processes were used to identify, determine and predict visual and thermal comfort performances of the selected options within the proposed space. Specifically, the study intended to predict possibilities of introducing roof elements to promote balance between daylight and heat gain. Harmony was also required between natural and mechanical ventilation, as this could improve the thermal comfort performance of a large area. Eventually, the process aimed to upgrade visual and thermal comfort performances in the covered atria.

The project is essentially a large covered atrium in a proposed large shopping complex in *Bukit Jelutong*, *Shah Alam*. It is currently completed in terms of construction. The original design of the covered atria or plaza is shown in Figure 1. As shown from the figure, the design represents part of large scale development of commercial and social urban space, with pedestrian circulation, and commercial stalls being proposed in the developing city of Shah Alam. The proposed development consists of blocks of 4-storey shop offices and commercial complexes at No. 6, Persiaran Pasak Bumi, Taan Bukit Jelutong, Seksyen U8, 40150 Shah Alam, Selangor, DarulEhsan. Built by Mainstay Development Sdn. Bhd, the covered atrium is located in-between the commercial blocks as shown in Figure 2.

Fig. 1: Space U8 _ original design without roof canopy

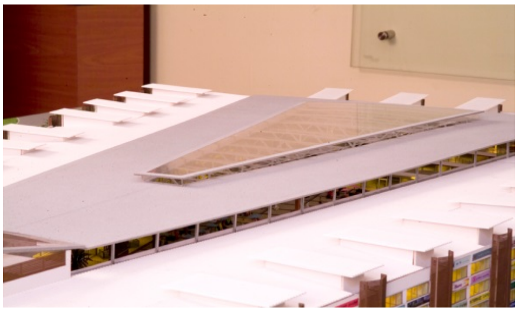


Fig. 2: Space u8-Original design with initial roof canopy design

Among the discussions made during the design process was to incorporate more openings at the top. This will allow hot air to escape through natural stack effect and also through wind driven ventilation to a certain extent. Such bioclimatic interventions may assist the building to ‘breathe’ besides balancing conflicting trade-offs in tropical climate. The improved options or interventions were analyzed and summarized as shown in the following figures:

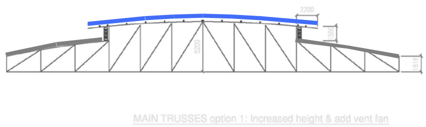


Fig. 3: The fully covered plaza option

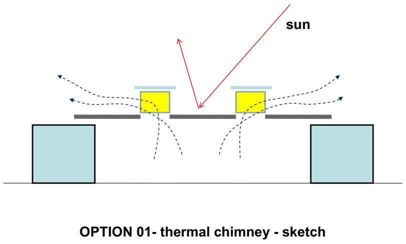


Fig. 4: The 1st Alternative option proposed

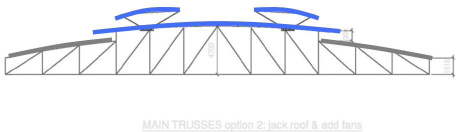


Fig. 5: The 2nd alternative option proposed

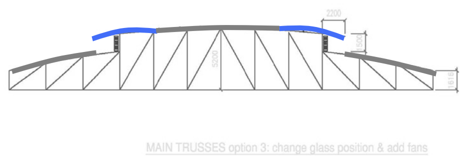


Fig. 6: The 3rd alternative option proposed

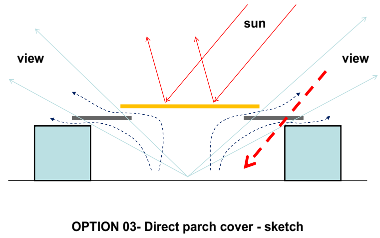


Fig. 7: The 4th alternative option proposed

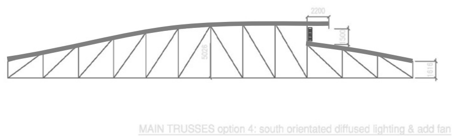


Fig. 8: The 5th alternative option proposed

2.1 Thermal prediction through simulation and analysis

To model ambient air flow, a simulation tool called Computational Fluid Dynamics (CFD) was utilized. This tool has demonstrated an efficient performance over conventional empirical and scale modeling techniques in terms of results accuracy and cost effectiveness (Neilsen et al., 2007 and Posner et al., 2003). Through detailed CFD simulations, all options were tested including the incremental effect of 'original roof' and 'improved roof', with more focus being directed to peak temperatures.

The simulations showed that (1) a combination of roof design that creates a jack roof between strips of roofs and (2) selection of low-e roof materials may result in internal thermal conditions of 30.2 °C. In contrast, covering the atria with a laminated glass roof or skylight would have created an internal thermal condition of 34°C, a temperature of 4 °C higher that the enhanced roof design.

The simulated results of the temperature and air flow distributions can be visualized as follows:

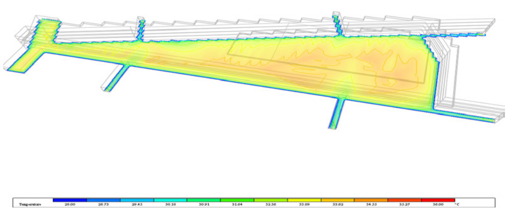


Fig. 9: Temperature distribution snapshot

at ground floor (+350mm) with Low-E glass

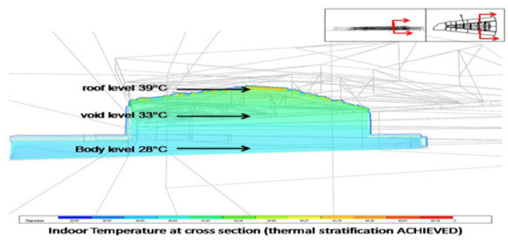


Fig. 10: Indoor temperature at cross section

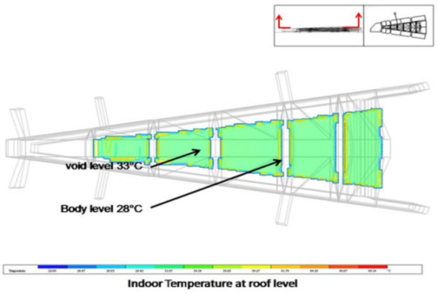


Fig. 11: Indoor temperature at the roof level

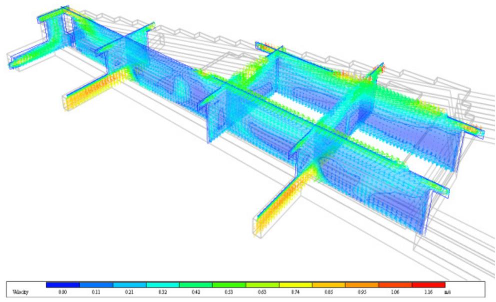


Fig. 12: Air flow distribution slicing through several sections within the plaza with low-e glass

2.2 Daylight simulation and prediction

To cut heat radiation, the researchers also had to balance between limiting heat gain through the roof and letting in sufficient daylight. Hence, daylight simulations were undertaken by using an advanced lighting tool called RADIANCE. The performance monitoring of daylight shows good agreement between simulation, predicted performance and actual performance. Figure 13 and 14 show the simulated results of daylight level in the courtyard.

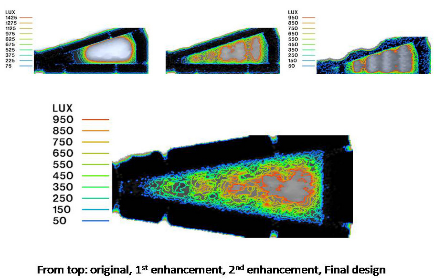


Fig. 13: 1st Enhancement, 2nd Enhancement, Final Design

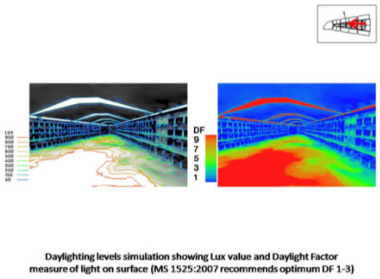


Fig. 14: Daylight level simulation showing the measure of light at the courtyard

2.3 Optimization of final roof canopy

A final improved design was configured based on thermal, economics and structural requirements and constraints as shown in Figure 15. This model consists of strips of skylights that are arranged in such a way to allow openings (like louvers) to be interspersed along the skylight. The improved design and roof performance is due to several thermal and heat transfer mechanisms and principles.

Firstly, lighter hot air at the top of the roof cover is given an outlet by the 'jack roof' elements. Thus, an escape mechanism is created between the strips of roof covers, where trapped hot air can be exhausted from the lower internal space. The outlet also creates pressure differences, or thermal buoyancy, that causes cooler air to replace the outgoing air. This thermal buoyancy then would create air movement that offsets the trapped heat from the covered atria.

Secondly, the low-E glass has a high efficacy value (high ratio of daylight admission and heat minimization). Low E is specified based on the requirement of admitting daylight. It also prevents heat gain from entering the space. In comparison, laminated glass has much lower efficacy as it does not effectively prevent heat transfer despite being used to reduce glare. The enhanced roof model, which uses the low-E glass roofs, has in fact recorded an internal air temperature of 1.6 °C. This is lower than the one recorded for the laminated glass option.

Fig. 15: The final design of the covered plaza and courtyard of Shopping mall

To cool the space further, air circulation systems and water features were strategically placed. As shown from Figure 16 and Figure 17, the installed fountains and suspended water walls represent passive humidification measures, which help to elevate the cooling effect by mean of convention. In fact, these features also enhance the interior's aesthetics and ambience.

Fig. 16: The Water fountain inside shopping mall courtyard

Fig. 17: The water feature inside shopping mall courtyard

3. MEASUREMENT AND MONITORING STUDIES

The post occupancy audit was carried out in two periods: 2011 and 2012. Apart from monitoring the performance of the final built plaza and shopping center, the audit also served to validate results obtained from thermal and daylight simulation tools. The audit was conducted for five days, on different periods of time throughout working hours as shown in Table 1. The 12 of HOBO™ Data Logger temp/RH was logged continuously for 3 days while the portable ALNOR Velometer AVM 440 was used to measure air velocity at 11.00 am and 2.00 pm daily. To measure indoor horizontal illuminance, a simple illuminance meter was utilized.

Table 1: Timeframe of post occupancy audit

Date	Starting Time	Finishing date
May 30, 2011	11:00 AM	June 1st, 2011
September 6, 2011	12:00 AM	September 9, 2011
March 18, 2012	10:50 AM	11:50 AM
March 20, 2012	3:45 PM	4:45 PM
April 8, 2012	5:35 PM	6:35 PM

3.1 Setup and location of on-site measurement points

As shown in Figure 18, the points for measuring temperature and relative humidity were located. The temperature was measured by utilizing the HOBO™ Data Logger temp/RH. For indoor measurement, horizontal illuminance was taken at specific testing points over three horizontal longitudinal axes from the atrium's south façade. The measurement was taken using a simple luminance meter located 0.8 m above the floor level.

Meanwhile, a short luminance measurement of glare or brightness was measured at specific testing points over five vertical longitudinal axes from the south facade of the atrium space beneath the atrium skylight.

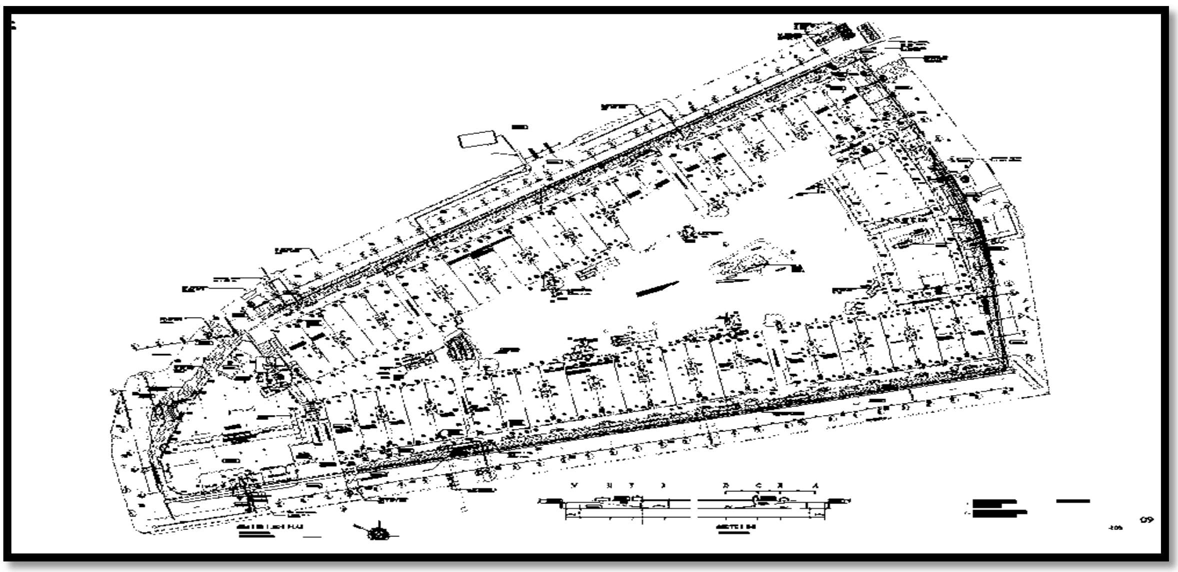


Fig. 18: Sectional axes to illuminance test points of measurment

4. POST OCCUPANCY AUDIT RESULTS

4.1 Air velocity results

The air velocity was taken at open air entry points of the ground floor. For simplicity purpose, the result is constrained at body level of the five points. Figures 19 and 20 show the air velocity results.

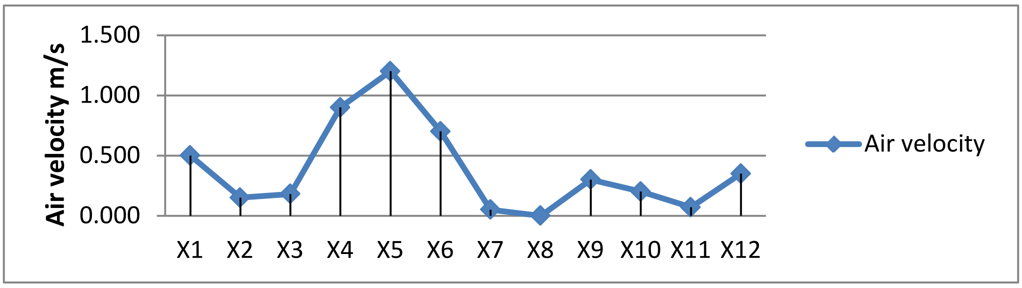


Fig. 19: Air velocity reading for 29/05/2011 – 2PM

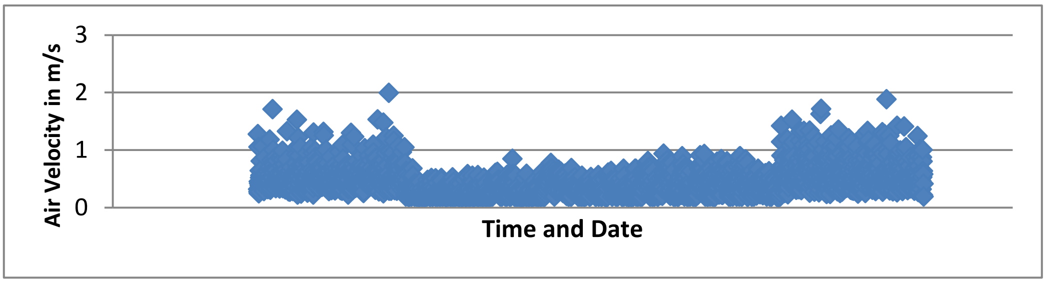


Fig. 20: Air velocity profile at middle of space u8 courtyard from 8th - 9th Sept 2011

4.2 Illuminance measurement results

The result of measurements of indoor horizontal illuminance can be highlighted as in Figures 21 and 22:

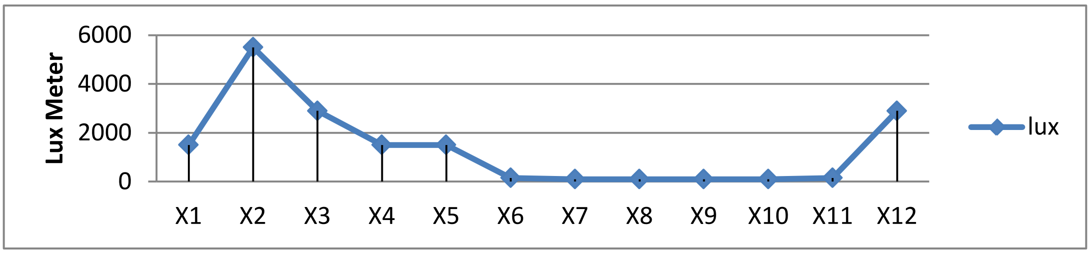


Fig. 21: Measurements of indoor horizontal illuminance on the 29/05/2011 - 11AM

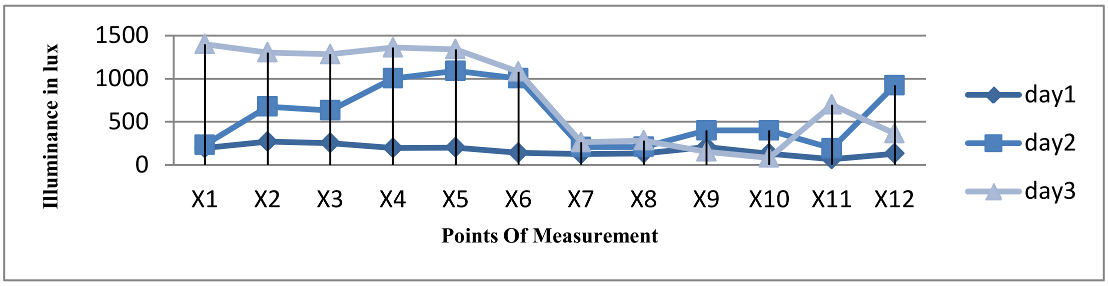


Fig. 22: Measurements of indoor horizontal illuminance on March 18 & 20, 2012 and April 8, 2012

4.3 Temperature audit result

Temperature results for the post occupancy can be shown in the following Figures and Table 2:

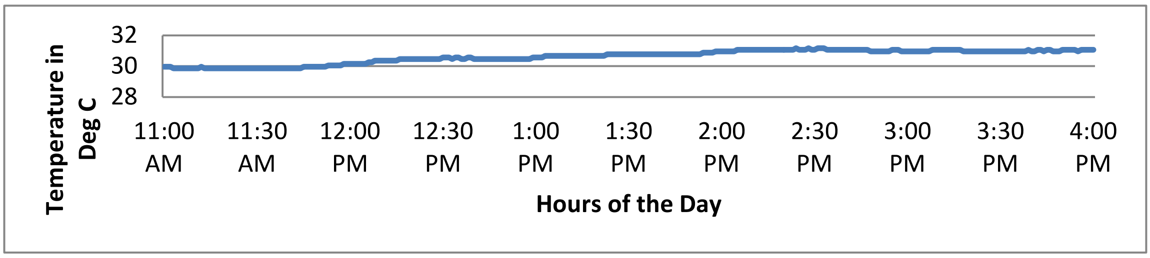


Fig.23: The reading for point 1 on the 30th of May

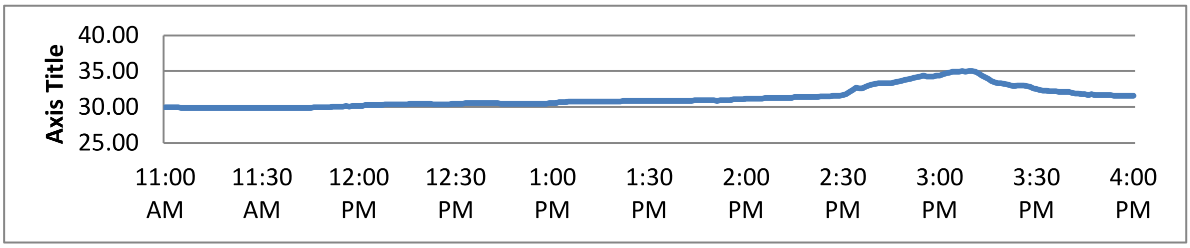


Fig. 24: The reading for point 2 on the 30th of May

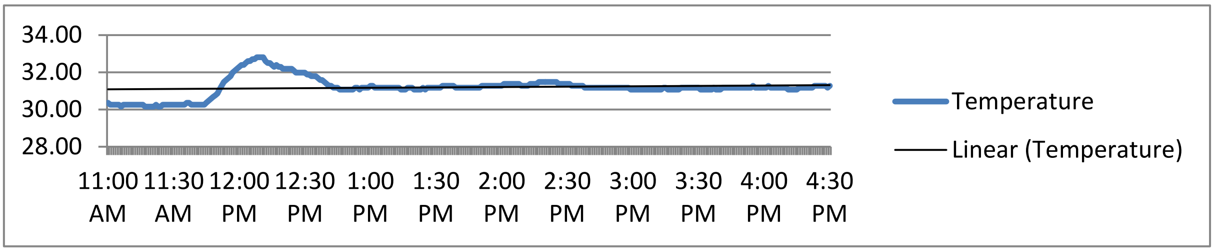


Fig. 25: The reading for point 3 on the 30th of May

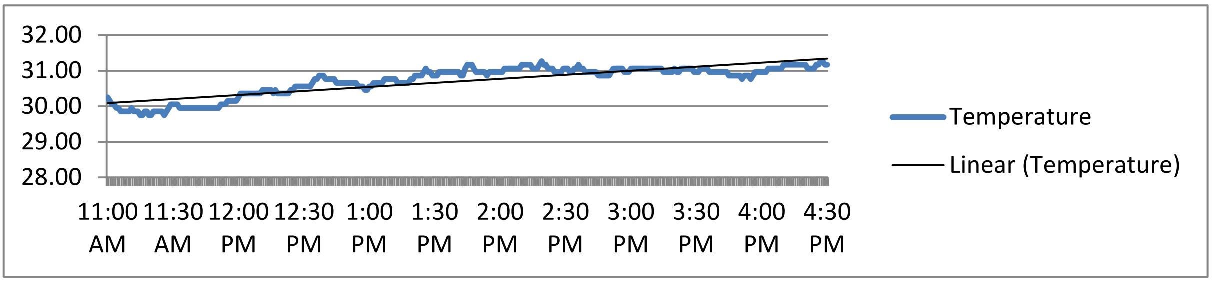


Fig. 26: The reading for point 4 on the 30th of May

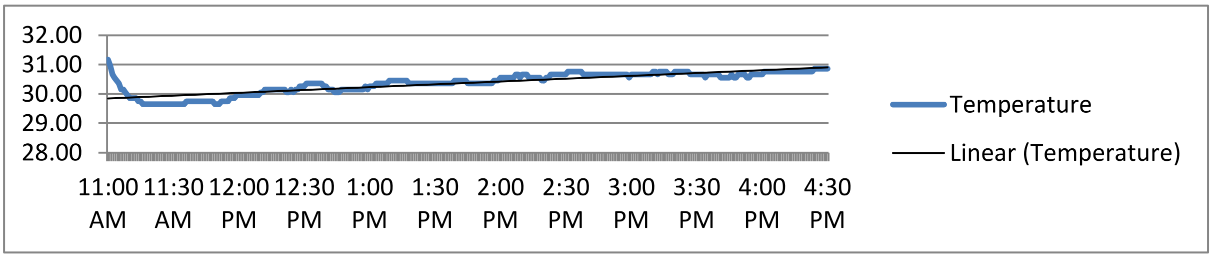


Fig. 27: The reading for point 5 on the 30th of May

Table 2: Outdoor and inside temperature on March 18 & 20, 2012 and April 8, 2012

Time	Inside	Outside
18/3/2012	30.1°C	32.4°C
20/3/2012	29.9°C	31.8°C
8/4/2012	29.4°C	31.3°C

5. PERFORMANCE AND OBSERVATIONS

5.1 Daylight Lux level

For all audit phases, the lighting conditions were well above expectations when compared to the simulation at working plane. At all test-points, the final results recorded more even distribution of daylight, with high levels being concentrated in the center. This distribution gradually declines towards western façade and gradually increases towards eastern façade. Table 3 and Figure 28 reveal the final results of measurements for indoor horizontal illuminance.

Table 3: Lux values for the building

Location		First day	Second day	Third day	Average
Working plane		2582.7	2549.3	1109.9	2080.6
Second floor	Minimum	172.0	292.7	176.8	213.8
	Maximum	286.0	323.5	191.5	267.0
Third floor	Minimum	220.0	228.5	135.5	194.7
	Maximum	256.0	337.5	222.0	271.8
Fourth floor	Minimum	176.0	299.6	177.8	217.8

	Maximum	286.0	376.4	209.5	290.6
Roof		2690.0	3607.5	1015.0	2437.5

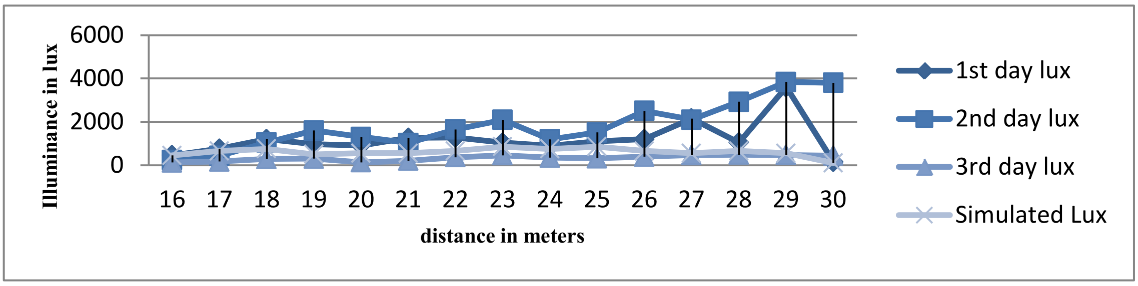


Fig. 28: Comparison between on-site measurement and simulated measurement

As for the lux level conditions at floor corridors, the simulation shows values that are close to 50 lux. The real minimum values were observed to be around 194 at the darkest spot. Those levels are well above the recommended average illuminance levels for corridors.

5.2 Air velocity

The results for air velocity were non-conclusive following the nature of the first audit; they may change once the mall operates. Regardless, the following results (Table 4) can be taken as an indication on how the building will behave under similar conditions.

Table 4: Summary of air velocity audit

Location		First day	Second day	Third day	Average
Ground floor	Main entrance	0.25	0.42	0.23	0.30
	Point 1	0.62	0.74	1.22	0.86
	Point 2	0.40	0.25	0.14	0.26
	Point 3	0.22	0.27	0.47	0.32
	Center	0.72	0.75	0.88	0.78
Second floor	Minimum	0.21	0.14	0.23	0.19
	Maximum	0.25	0.42	0.34	0.33
Third floor	Minimum	0.14	0.08	0.14	0.12
	Maximum	0.20	0.24	0.28	0.24
Fourth floor	Minimum	0.29	0.22	0.14	0.22
	Maximum	0.09	0.14	0.07	0.10
Roof		0.47	0.34	0.31	0.37

As shown from the data, maximum air velocity recorded was 1.63 m/s, a speed considered at the upper range of comfort but is acceptable in hot and humid conditions. On the other hand, the average air velocity in the building was 0.47 m/s, a speed considered quite stagnant and unpleasant in warm condition, but is acceptable in cool conditions.

5.3 Temperature results

The temperature at the plaza confirmed the previous simulation. Although the simulation temperatures were not impressive, they are still considered within the comfort level. It was also predicted that the plaza will eventually have better temperatures when the fountains, air circulation systems , and spot cooling points (entrances) operate. The audit also shows that for a variation of time and external weather conditions (ranging from rain and cloudy days), internal temperatures (at peak time of 2pm in the day) may range from 28 ℃ to 30 ℃. Regardless, air velocity and temperature have no correlation in change. Table 5 shows the summary of recorded temperatures.

Table 5: Temperature summary

	Working plane temperatures			Average
Minimum	29.85	29.13	27.39	28.79
Maximum	32.28	30.13	27.87	30.09
Average	30.82	29.83	28.36	29.67
	Roof level temperature			Average
Minimum	30.46	30.46	26.98	29.30
Maximum	35.12	32.50	26.98	31.53
Average	33.49	31.49	28.53	31.17

The audit also found that at 2pm, an average of 29.7° C was observed at body level in the majority areas within the plaza. This coincided with the acceptable thermal comfort range based on 60-70% RH (Relative humidity) and sufficient air flow under Malaysian climate. However, these temperatures may also be affected by airflow and relative humidity conditions. Comfort levels in the tropics can thus be improved by increasing airflow through mechanical means.

6. CONCLUSION

Thermal consideration of outdoor environments in large cities is essential as it adds value to urban space. Because comfort contributes to people’s life, thermal comfort then, contributes to the quality of a space. The comfort conditions within these spaces are affected by urban design parameters, morphology of buildings, characteristics of surrounding surfaces and spaces, in addition to occupant activities. Therefore, understanding of convective and radioactive exchanges through the actions of wind, as well as the differences in temperatures and pressures can contribute towards enhancing a microclimate necessary for urban life patterns in the tropics.

Hence, strategic design was undertaken that involved ‘breaking the roof section and overall area’ into ‘smaller strip of glass and metal deck roof’. This will reduce heat penetration to the space and will allow the latter to ‘breathe’. Jack roof effect will help to provide an outlet for the trapped heat under the roof covers. Glass roof with low-e properties will help to prevent heat from entering the space in addition to allowing sufficient daylight. To assist the cooling further, water features and air circulation systems were strategically placed.

Until today, no air-conditioning is used in this space and the retail mall visitors were delighted to experience breezy and cool atmosphere. One of the visitors commented in her blog:
‘…Apa yangaku perasan, dekat dalam ni takde menggunakanaircond.Maybe dalam shop lot tu diorang gunaaircond. Dekat luar2 ni, terasa cam berada dekattepi pantai. Berangin dan xterasa bahang p

anas.Padahal kat luar tu panas terik…' Translation *"what I can see definitely from this shopping centre is… the internal area of the shops use air conditioning, but the common areas.. It feels like near the beach… you can't feel the heat radiation at all, whereas the outside is intense heat…"* The project represents a strategic usage of simulation and visualization tools in energy efficient design. On completion of the building, two phases of Poe confirmed that the simulation tools closely reflected the actual environment within the commercial centers.

7. REFERENCES

Hung, W.Y. and W.K. Chow (2001). A Review on Architectural Aspects of Atrium Buildings. Architectural Science Review, 44 (3): p. 285-296.

Nielsen, P.V., Allard, F., Awbi, H.B., Davidson, L. and Schälin, A. (2007) Computational fluid dynamics in ventilation design. REHVA Guide Book 10. RHEVA (Federation of European Heating and Air-Conditioning Association), Brussels. ISBN 9782960046892

Posner J.D., Buchanan C.R., Dunn-Rankin D. (2003) Measurement and prediction of indoor airflow in a model room, Energy and Buildings, Volume 35, 515–526

Sharples, S. and D. Lash (2007). Daylight in Atrium Buildings: A Critical Review. Architectural Science Review, 50.4: p. 301-312.

MALAYSIAN INSIDER NEWSPAPER, Saturday, April 22, Eco roof helps new mall beat the heat.

THE CONCEPTION OF MAKING DECISION SUPPORT SYSTEM INTRODUCTION INTO BUILDING STRUCTURES DESIGN PRACTICE

Vladimir Alekhin & Anna Khanina
Federal State Autonomous Educational Institution of Higher Professional Education «Ural Federal University named after the first President of Russia B.N.Yeltsin», Yekaterinburg, Russia

ABSTRACT: *The paper discusses introduction of artificial intelligence into structural engineering practice. The necessity of this paper is accelerated by the information base (IB) and decision support systems exigency, as some standards are not completely designed and there is no statistical information on faults, defects and damage to various buildings. The article suggests creating a decision support system for the optimal structural design of buildings that takes into account a risk of a propagating rupture. The article describes possibilities of a decision support system, the stages of its development and structure. Conceptual solution of the proposed decision support system for the analysis of structures is illustrated by designing trade and business centre high-rise building. The system is based on a knowledge base, which is created during its development and can be updated and expanded with the advent of new codes of practice and new structural design recommendations. Expert system will be built on the basis of clear rules and recommendations from foreign and Russian codes of practice, as well as European standards, and international occurrences of buildings accidents. Optimization of structural elements is performed on the basis of a genetic algorithm. The effect of various genetic operators on the performance of the algorithm is investigated. A model of a genetic algorithm for optimization of steel structural elements is developed. The work is the attempt to create a complex approach to the structural design: the user can not only study the normative documentation, get advice, study the examples of calculation, but also take advantage of the proposed programs for the optimization of the design decisions. It is expected that expert's knowledge on the analysis of buildings incorporated in expert system will improve the quality of the design, and as a consequence, the reliability of structures.*

KEYWORDS: *decision support systems, expert systems, optimum design, propagating rupture, genetic algorithm*

1. INTRODUCTION

The problem of safety and efficiency of buildings and structures is one of the main problems highlighted by continuously increasing volume of construction. The research in the design of reliable and at the same time, the optimal building structures indicates the relevance of creating expert systems in design. It is necessary to solve the problems that structural engineers are facing today. An urgent need for an information base (IB) and decision support systems is escalated. This paper proposes the creation of decision support expert system (ES), which will provide access to necessary information and suggest ways to solve problems effectively. In the U.S.A., Germany, Japan and other developed countries, hundreds of decision support systems of intellectual type (based on the ES) have been already designed and are used in various areas of construction. In Russia, expert systems are mainly used in the construction investment process.

2. BACKGROUND OF THE ES CREATION

The reference article (Gurjev and Dorofeev, 2006) states that in order to make effective decisions on reducing the occurrence of accidents in areas subject to natural and anthropogenic hazards, objective information about the technical state of objects can be obtained by monitoring the strength resources of buildings and structures. Currently the technology that monitors existing structures in the world is in a conceptual development stage, although some recent unexpected collapse of buildings in our country and abroad brought this problem to the foreground of preventive measures that ensure the safety of the population, especially in major cities. This information database is created by studying technical conditions of actual structures serving various purposes

Citation: Alekhin, V. & Khanina, A. (2013). The conception of making decision support system introduction into building structures design practice. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

and by analyzing the conditions of their performance. In addition, the use of statistical information on faults, defects and damages received as a result of technical inspection of objects of the same type, will help to develop a structural reliability model and solve the problem of minimizing total expected costs, namely the cost of construction and maintenance of the structure.

In recent years, our industry discussed actively the design of structures taking into account a risk of cascade collapse. However, the design standards on this issue are not fully developed, while engineers need an improved methodology for assessing the vulnerability of structural systems and their improvement to mitigate damages from cascading collapse in various collapse scenarios. A very relevant issue is the optimal design of structures based on their joint work with the foundation.

One of the prerequisites for creating an ES is a decision-making under uncertainty. The creation of databases which will contain design examples, patents, books, containing solutions to overcome difficulties, is proposed.

3. CONCEPTUAL SOLUTION OF THE PROPOSED EXPERT SYSTEM

The concept of rapid prototyping was used for the development of expert system. The essence of this concept is to develop an ES's prototype in a short time, which is designed to implement a limited number of tasks. A prototype of expert system was created on the basis of the typical ES structure (Fig.1).

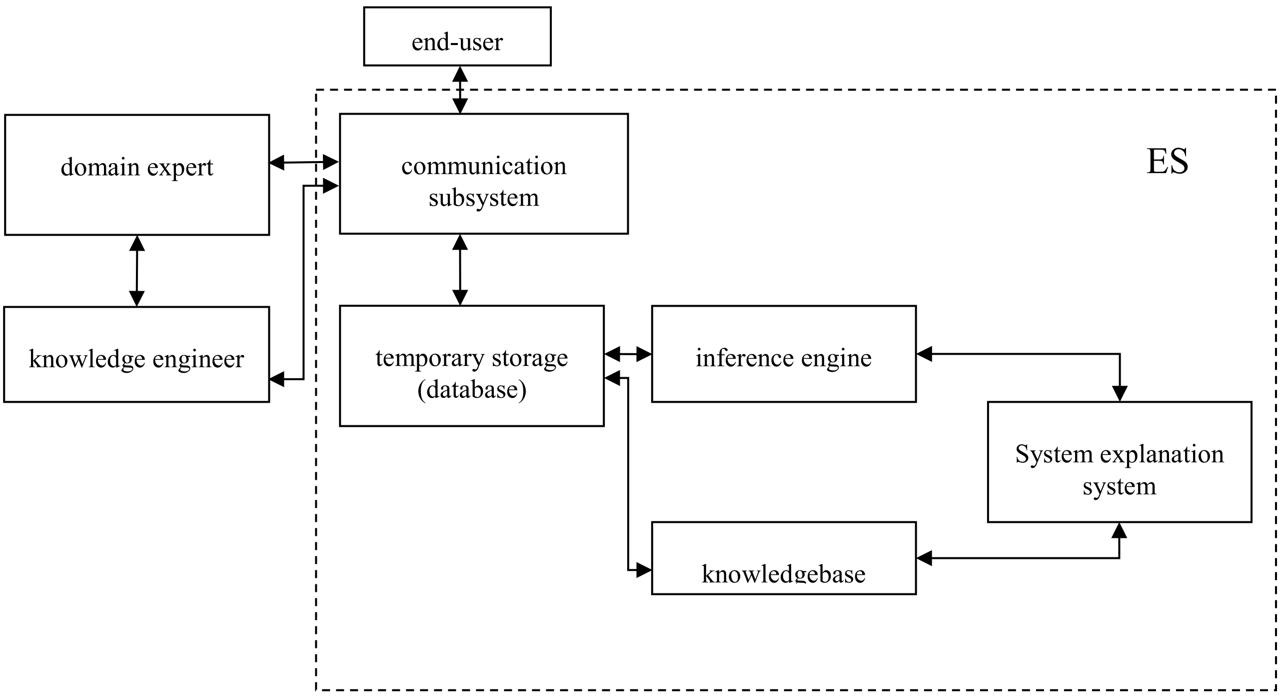


Fig. 1: The structure of the expert system

Numerous works were studied (Chris Naylor, 1991; Jean-Louis Lauriere, 1991; Peter Jackson, 1998 and others). The program was created similar to Leonardo expert system. Software was written in Delphi. Knowledge can be represented as both rules and frames. A frame represents an object or situation by describing the collection of attributes that it possesses. It does this by listing all the attributes of a typical case, and by providing a slot for each one. This description of the typical case then can be used to capture any individual case by placing the value of its attributes in the respective slots. Each frame has a standard set of slots into which information about the object can be entered. The slots are as follows (LEONARDO Revision 3.20, 1990):

- Name: name of the object;
- LongName: more descriptive name;
- Type: text, list, real;
- Value: value assigned to the object;

during last consultation

- Certainty: between 0 and 1 expressing the certainty with which the value is believed to be true;
- DerivedFrom: Source of the value in the Value: slot;
- DefaultValue: value assigned to the object if the user responds to user query with unknown or user query is suppressed;
- FixedValue: Specifies an initial value for an object.

  Can be changed later;
- AllowedValue: Contains the permitted values for an object;
- ComputeValue: Contains the name of a procedure. A procedure is a piece of executable code that will derive a value for the object;
- OnError: Defines a message which appear if the user supplies a value which is outside the specified AllowedValue;
- QueryPromt: Contains a text promt used when the user is asked for a value;
- Commentary: Slot for system builders notes;
- Introductions: Appears when the application is started;
- Conclusion: Screen format which is displayed when the object is instantiated;
- Ruleset: This slot contains a set of rules in similar format as the Main Ruleset for instantiation of the object. These rules can be used to derive a value for the object.

Knowledge can be represented with rules of the general form: IF condition (or consequent) THEN action (or antecedent).

However, there is a fundamental difference. The developed program feature consists of two independent modules: knowledge base editor and expert system shell. The system is based on a knowledge base, which is created during its development and can be updated and expanded with the advent of new codes of practice and new structural design recommendations. Knowledge base is being developed in cooperation with leading experts; it presents a set of qualified opinions (rules) and a constantly updated directory of the best methods and strategies used to solve specific problems. Expert system will be built on the basis of clear rules and recommendations from foreign and Russian codes of practice, as well as European standards, and international occurrences of buildings accidents. The main window of the editor of knowledge base is shown in Figure 2. Editor is designed to create, edit and save the files of knowledge-base on drive. Database files created in the editor at any time can be downloaded to add new information or edit an existing one. Files of database which were created in the editor can be uploaded at any time to add new information or edit an existing one. Knowledge-base editor user - is the knowledge engineer.

The prototype of ES was created by the example of consultation on the issue of disproportionate collapse. The expert system shell is designed for the end user. Expert system shell window is shown in Figure 3.

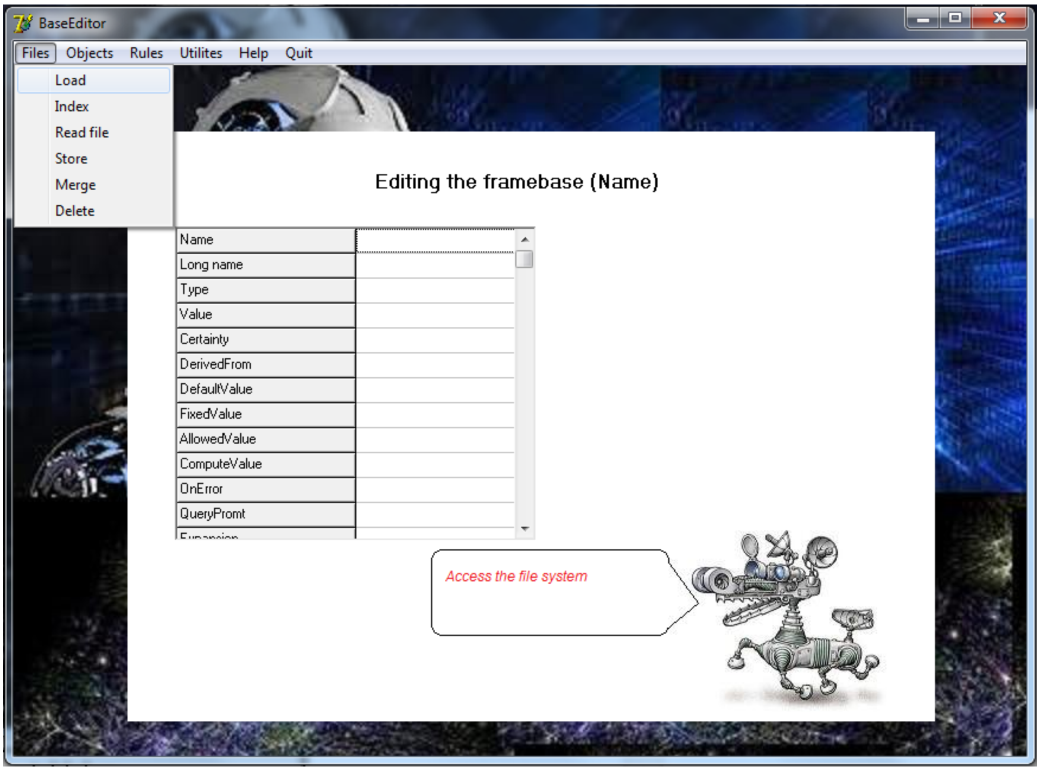


Fig. 2: The main editor window of knowledge base

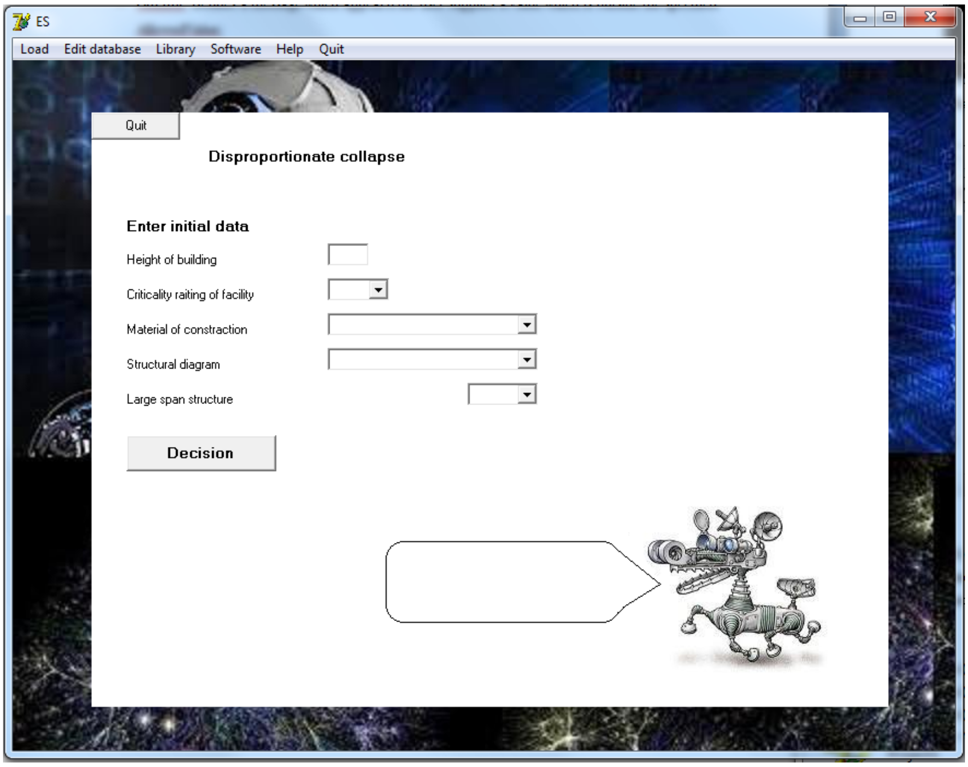


Fig. 3: Expert system shell window

Expert System will help to assemble and categorize the required initial information on an object: type, size, number of stories, level of responsibility, functional purpose, the specifics of the processes which will take place in it, location, soil conditions, location, etc. If necessary, IB will be defined. The problem is formalized by the dialogue with the user on the scenario approach and knowledge of ES base. As fairly pointed out in (Perelmuter and Slivker, 2007), if a structure is small, e.g. its dimensions are comparable with the size of the "local" damage, then it will not make sense to check the possibility of progressive failure. According to the classification of buildings and structures, the selection of objects for analysis is carried out based on:

- Objects of class 1, for which the design does not consider a possibility of accidents
- Objects of class 2, in which all structural components can be protected from accidental damage by increasing the carrying capacity or the use of protective devices;
- Objects of class 3, in which some structural elements cannot be protected from accidental damage, which would require assessment on the progressive destruction (Perelmuter and Slivker, 2007).

In the next step block solver ES classifies the building based on the size of the considered structures, and potential emergencies, according to data entered by the user. ES in consultation with the user selects one of three possible options: design of the structure without considering disproportional collapse; design of structure without considering the disproportional collapse with indication of possible preventive measures to protect the structure or design of the structure in view of the emergency situation, but preserving the integrity of the structure; and the third alternative is calculation accounting for the disproportional collapse of the structure, i.e. by removing some elements from the design model. Deleted elements are selected depending on the background information about the object. It means that, for example, if explosives are placed in a building, elements closest to the explosive location will be more vulnerable. Design of the structure is carried out with regard to the possible destruction of these elements.

All directions to correct initial design model that are received from the ES (emergency impact load, exclusion of certain elements from the model) can be used by user and applied to calculate the structure in one of the available computational software systems.

The prototype of the proposed decision support system for the analysis of structures has been considered and tested on the example of designing a high-rise building for trade and business center (e.g. Figure 4) with regard to the risk of its progressive collapse.

Fig. 4: The general shape of the building trade and business center in Yekaterinburg

Load-bearing frame for the 38-story section is a supported framework, with the external shank in the form of a truss. The overall stability of the building is provided by the columns, non-divided floor structure plates and vertical space truss, which is a system of vertical cross braces of auxiliary bars, and is placed on the perimeter of the building. Vertical load is carried by the columns; horizontal load is transmitted to the truss through floor structure.

At the first stage, which is the stage of identification, the tasks were defined: establishing recommendations for design of the structures with regard to the risk of the propagating rupture, and issuing reinforcement recommendations for the structure. The process of expert system prototype development was planned, necessary sources of references (books, design standards, methodology), resources, similar expert systems, goals, etc., were identified.

At the second stage, the stage of conceptualization, the structure of the identified information about the subject area has been revealed. Terminology, a list of the main concepts and their attributes, the structure of the input and output information, decision-making strategy, etc., were defined. At this stage the main concepts and the relationship between the concepts of the subject area were also defined.

At the stage of formalization the attempt was made to express all the key concepts and the relationships identified at the stage of conceptualization by some formal language. The main component of the knowledge base is a set of rules. As a base of procedural knowledge, the system has a set of products (rules) of the type IF A, THEN B.

At the stage of implementation, the prototype of expert system was created, which included a knowledge base and other subsystems. The fourth stage of expert systems development, to some degree, is the key, as it is the stage of bundled software creation, which is demonstrating the viability of the approach as a whole.

At the fifth stage, the stage of testing, the prototype was tested for usability and appropriateness of the I/O interface, the effectiveness of management strategies, the quality of the test examples, and the correctness of the knowledge base.

According to the logic of the expert system, the low stylobate part was classified as the object of class 1, meaning it was not taken into account when calculating an emergency situation. It was designed without measures to impede the propagating rupture. Since the high-rise part was of the level I importance and was more than 75 meters in height, it was assigned an object class 3. It had to meet special requirements on the stability against a propagating rupture, and structural calculations considered the probability of failure in any of the load-supporting elements.

As a result of consultation with the ES, were received the following recommendations. The building contained no explosive manufactures, accumulation of combustible materials, or other hazardous substances. Therefore, types of local structural failure should be defined as usual, according to (Shapiro et al., 2006). As the most dangerous types of local structural failure, the failure of any free-standing column and the collapse of floor plate with the area of 80 m2 should be considered. Only dead-loads and long-time temporary loads should be taken into account while computing against the propagating rupture.

Types of floors, where destruction should to be modeled: all different floors with a reasonable classification. The most dangerous locations of local damage are: the destruction of the corner columns, the destruction of the all four corner columns of the building, several middle columns and columns at the extreme perimeter of the building in areas of largest cantilevers of floor structures. Collapse of the overlying floor area should be at the end bay and in places of the greatest floor cantilevers. Loads for the computation of the building in an emergency phase should take the following: according to (Shapiro et al., 2006), analysis taking into account the local destruction must be performed on special combination of loads, which includes the permanent loads with their design value, long time temporary loads (temporary loads with low design values) and one emergency impact. Combination coefficient of all the loads is equal to 1.

Computation of framework on the resistance against the disproportionate collapse was performed with the help of the bundled software "Lira 9.4". Stresses in separate elements of the structure, obtained on the basis of static calculations with the account of the local collapse were compared with the stresses from static calculation results without regard to local collapse. The results of the calculations revealed that the local collapse did not lead to a structural failure of the neighboring vertical structures and the disproportional collapse of a building. The most adverse schemes of local collapse for the vertical supporting elements were the destruction of columns at the perimeter of the building, especially the corner columns.

The computations showed that the collapse of overlying floor structures with area of 80 m2 was not a dangerous scheme of local collapse. Stresses in the floor structure elements did not exceed acceptable values. It was revealed, that the design of the floor structure was not protected from the propagating rupture when the collapse of the separately standing columns occurred. However, beams inflexibly connected with the columns could continue to work effectively with formation of large bays and cantilevers in the system.

In accordance with the expert system concept, the design of structure reinforcement was developed to protect the floor structures from a propagating rupture. According to (Shapiro et al., 2006) it allowed for rigid connections of beams to columns. In addition, it was required to increase the reinforcement in the flat part of the floor. Originally, the project was designed with the upper background reinforcement continuous throughout the floor area Ø5 V500 (Bp-I) at 400 mm in both directions. It was replaced with a Ø10 A400 (A-III) at 200 mm in both directions. The spacing of the lower concrete reinforcement was also reduced to 200 mm from the initially designed Ø10 A400 (A-III) 400 mm on center, since the failure of any column or relative settlement in the area of a column would require more lower reinforcement. At the corner areas of floor structures, the local reinforcement was also strengthened. A number of design solutions, impeding to the propagating rupture was also included. For example, anchoring lower reinforcement in the area of concrete reinforced beams is carried out by welding.

Thus, in the process of the user's work with the ES, the decision support system summarizes existing knowledge in its database and offers the user the rational way to solve problems, displaying a chain of reasoning and references to sections of regulatory documents. By using the module-based optimization of genetic algorithm, the problem of finding optimal or near optimal settings of the optimized cross-sections of the structure can be solved.

Once the prototype was tested on the suitability of the system to work in this domain, the correctness of the code, the encodings of the facts, links and strategies reasoning of the expert, in the ES were included the following sections: library, consultation, the design approaches on the progressive collapse, examples of the analysis, analysis and optimization of structures. "Library" includes domestic and foreign requirements documents relating to the protection of buildings against progressive collapse (e.g. Figure 5).

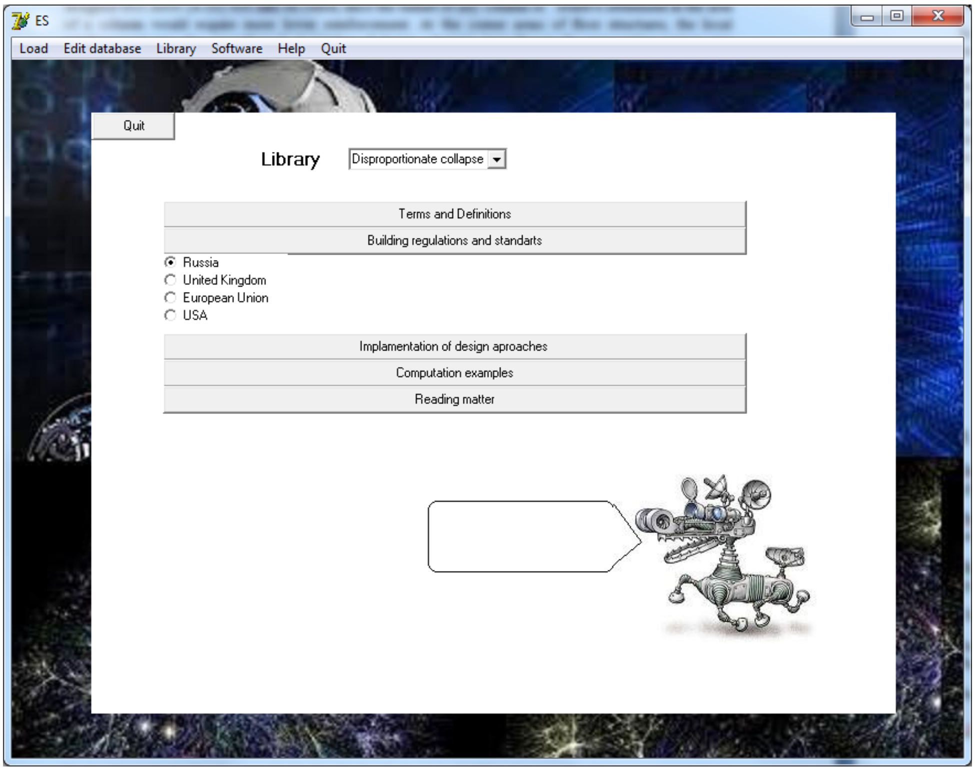


Fig. 5: Library of ES

Section "consultation" is the core. In the "methods of calculation" different ways of analysis are presented in schematic form, briefly it is described how these methods are implemented. In the section "Examples of analysis" one can see examples of computations by different methods of structural analysis. In the "analysis and structural optimization" the user can take advantage of the developed programs for the structural optimization, for example, program of optimization of constructions on the basis of a genetic algorithm (GA). GA is a well-reputed heuristic solutions search method. Definition of the optimization problem is expressed by determining design parameters {x1 ... xn} for elements of steel frame buildings using a minimum volume of structure criteria and complying with limitations on strength, stiffness, local and general stability.

Based on studied publications and tests of the algorithm, the following model of the GA is suggested: the initial population is randomly generated; population size and capacity of the genes are fixed. The selection is proposed as elitist, a method of parent-pair forming is a genotypic outbreeding. Crossover operator of individuals is encouraged to take a single point, and the mutation operator with probability of mutation is of the order of 3%.

4. CONCLUSION

In conclusion, the work is the attempt to create a complex approach to the structural design: the user can not only study the normative documentation, get advice, study the examples of calculation, but also take advantage of the proposed programs for the optimization of the design decisions. In future it is planned to create a database of statistical information on structural failure, defects and damages received on results of the technical examination of objects of the same type; to expand the circle of tasks, and add to the base constructive examples, patents, books, in which there will be a way of overcoming some of the difficulties. It is expected that expert's knowledge on the analysis of buildings incorporated in expert system, will improve the quality of the design, and as a consequence, the reliability of structures.

Here are a few possibilities of ES:

- optimization of the design decisions for buildings at the early stages of design, the choice of the basic space - planning decisions for buildings (configuration, column grid, structural solutions);
- making effective decisions to reduce the emergency situation occurrences in regions subjected to natural and man-made hazards;
- design in terms of reliability, taking into account the probability of structural failure after a certain operating duration and accounting for relevant maintenance;
- the possibility to use probabilistic methods of structure optimization;
- design of structures with regard to the risk of their disproportional collapse;
- decision-making in conditions of uncertainty; optimization of structures based on modern methods of optimization by genetic algorithms;
- competent user help, design standards reference.

5. REFERENCES

Chris Naylor, (1991). *Build your own expert system*. John Wiley & Sons Ltd, Chichester.

Gurjev V.V. and Dorofeev V.M., (2006). *Monitoring of buildings and facilities, ensuring the safety of long-span structures. Industrial and civil construction*, №4, 24-25.

Jean-Louis Lauriere, (1991). *Intelligence Artificielle. Resolution de problemes par lhome et la machine*, Eyrolles, Paris.

LEONARDO Revision 3.20. Documentation Supplement. Creative Logic Ltd, 1990

Perelmuter, A.V. and Slivker, V.I., (2007). *Computational models of structures and the possibility of their analysis*. Moscow: DMK Press.

Peter Jackson (1998). *Introduction to Expert Systems*, ISBN 0-201-87686-8

Shapiro, G.I. and Travush V.I., (2006). *Recommendations for the protection of high-rise buildings from the progressive collapse.* Moscow

THE APPLICATION OF CLOUD COMPUTING IN TRANSPORT PLANNING USING INTERACTIVE 3D VR SIMULATION TECHNOLOGY

Yuji Ito, Christophe Soulier & Yoann Pencreach
FORUM8 Co., Ltd., Nakameguro GT Tower 15F, 2-1-1 Kamimeguro Meguro-ku Tokyo, Japan

Brendan Hafferty & Patrick Hafferty
FORUM8 Western Regional Office, UK Fleet House, New Bridge Street, London, UK

ABSTRACT: *The design and planning of urban and transport infrastructure has undergone a tremendous transformation over the past few years. Not only has the available software technology changed considerably, so have the requirements and demands of the various stakeholders. As the democratic process becomes even more open, coupled with the advent of 24/7 information and news, so the demands of the general public to have a greater say in the actions that have a direct effect on their lives have increased. Local and National Government planning professionals are under increasing pressure to not only justify what they plan to do in words and pictures, but also to show the proposed new developments in a medium that is far more easily understandable to the ordinary 'man in the street'. In the recent past the only way to do this was by calling 'town hall meetings' and displaying large photographs, video clips or solid models. This paper describes a new and novel way to improve consensus building for contentious new infrastructure projects, by using Interactive 3D Visual Simulation computer models, delivered to the target stakeholder community via the Cloud.*

KEYWORDS: *3D, Visualization, VR, Cloud Computing, Urban Planning, 3D City Modeling, Consensus Building*

1. INTRODUCTION

According to the well-known computer analysts Gartner Inc., "…cloud computing heralds an evolution of business that is no less influential than e-business." Gartner maintains that "…the very confusion and contradiction that surrounds the term 'cloud computing' signifies its potential to change the status quo in the IT market."

The key point here being the use of the ubiquitous Internet to communicate and obtain on-line responses from and with multiple external people – in this particular case - stakeholders i.e. transport planners in different office locations, local & national government officials, the local business community & members of the general public.

The objective of this paper is to show how the use of the very latest interactive 3D software can be integrated into the very latest Cloud Computing technology and in so doing expand the consensus building process to anyone with access to the Internet (Conway G. 2011).

This objective will be achieved through the development of a new product called VR-Cloud, part of the family of Virtual Reality (VR) products produced by the Japanese company FORUM8. The aim is to complement the company's leading Interactive 3D Visual Simulation & Modeling software VR-Design Studio (formerly UC-win/Road), by enabling its 3D interactive environments to be accessed and manipulated over the Cloud.

The ultimate aim being that anyone with Internet access will be able to view new transport and infrastructure developments and even walk or fly through the proposed new 3D Space at will. No longer will they have to rely upon fixed views of new buildings, tunnels, bridges, highways etc., they will be able to experience what the new environment will actually be like within the virtual environment of their own PC or indeed Android.

One of the key benefits of using the Cloud to deliver these 3D VR environments is the fact that the stakeholder (member of the public or indeed any other interested party) does not require any special hardware. All they need is good Internet access.

Citation: Ito, Y., Soulier, C., Pencreach, Y., Hafferty, B. & Hafferty, P. (2013). The application of cloud computing in transport planning using interactive 3D VR simulation technology. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

2. TRANSPORT PLANNING

2.1 Background

Transportation planning in the United States would appear to be changing with respect to its involvement with stakeholders. As in the UK and in many ways following the lead given by some European countries, the US urban planners seem to be moving away from the simplistic solution of simply moving traffic from A to B and towards a more holistic approach that takes into consideration the communities and environment through which the traffic has to pass. In addition this more enlightened approach would seem to place greater emphasis on rail and light rail (tram) networks, bicycle lanes and other forms of public transport as well as pedestrian movement (known in the UK as walking strategies).

These new ideas are in many ways not new. In 1998 there was a conference in the State of Maryland titled "Thinking Beyond the Pavement". The aim of this conference was to promote the concept that transport projects had to preserve and enhance the natural and built environments, as well as the economic and social assets of the neighborhoods they pass through.

These principles have since been adopted as guidelines for highway design in federal legislation. Since then the Federal Highway Administration set a target for all DOTs to adopt these new guidelines by 2007.

2.1.1 The Technical Process

Most regional transportation planners today employ what is called the rational model of planning. This process uses the analysis of quantitative data to decide how to best invest resources in new and existing transportation infrastructure.

Over the past 50 years both in the US and Europe there has developed a reliance of the use of travel modeling as a major element in the overall transport planning process. As the volume of vehicles on the roads and highways (motorways) increased, almost exponentially, so the reliance upon such modeling techniques increased accordingly.

The problem is that transport planning by its very nature is based on predicting the future and hence is not and cannot be 100% accurate.

As complex micro-simulation computer technology has become the norm in predicting traffic demand throughout the western planning community, so there is a great danger in assuming that the output of these simulations is an accurate reflection of what will actually happen if the proposed infrastructure changes take place.

This particular problem was highlighted by the study of Flyvbjerg, Skamris Holm and Buhl (Flyvbjerg B. 2005). In this study the authors found that many of the models that planners use to promote and secure large scale highway and rail projects are fundamentally flawed and often grossly inaccurate.

It is therefore particularly important that urban planners understand the concept of GiGo (garbage in – garbage out) and insure that their 'models' reflect all the available data and the various planning guidelines and the views of the customers i.e. the public – for whom they work.

A large part of transport and general urban planning involves this technical process that is designed to predict where future investment needs to be made. However it's very important to understand the public involvement implications of this process.

As planners become to rely more and more on complex technical tools such as micro-simulation modeling software so it becomes more difficult for members of the public to understand all the technical issues and actually visualize what the proposed changes will look like and how they will affect their 'way of life' and home environment.

Indeed, it is not only the general public that find it hard to visualize new infrastructure projects, local and regional government politicians, who ultimately make the investment decisions on behalf of the public, often cannot understand all the features and benefits of such projects.

2.1.2 Stakeholder Consultation

This leads me to highlight the involvement of the public and the changes that have taken place in the way planners view the public and other stakeholders, particularly in Europe, and particularly since the 1960's.

Too often in the past there has been an attitude of 'we the professionals' know best. We know what's good for the community, we know how best to plan for the rise in population or the increased traffic congestion.

Far too often architects have been allowed to change the face of towns and cities without any level of consultation with the people who live and work within these built environments. Once again the 'professionals' know the best type of material, shapes and sizes that these new buildings should be constructed from etc.

As has been proven in many towns and cities throughout the west, especially in the industrial cities of the UK, this approach has led to urban decay. Whole communities have been demolished simply through the hubris of professionals, allowed by weak local officials and politicians to do precisely what they wanted without any thought to how it would actually affect the 'stakeholders'. In fact the term stakeholder is rather a new one as is the concept of consultation and consensus building.

2.1.3 Consensus Building

Stakeholder consultation and consensus building are really about initiating and sustaining constructive external relationships over time. Organizations that start the process early and take a long-term, strategic view are, in essence, developing their local "social license to operate." so said the International Finance Organization – part of the World Bank Group (IBMTech 2010).

For infrastructure projects that have an environmental and social impact, such consultation should not be a single conversation but a series of opportunities to create understanding about the project among those it will likely affect or interest, and to learn how these external parties view the project and its attendant risks, impacts and opportunities.

Listening to stakeholder concerns and feedback can be a valuable source of information that can improve project design and outcomes and help to identify and control external risks.

For stakeholders, the consultation process is an opportunity to obtain information, as well as to educate the professional planners about the local context in which the proposed project will take place, to raise issues and concerns, ask questions, and potentially help shape the project by making suggestions.

2.1.4 Sustainable development and sustainability

There has been a significant growth in the concept of sustainable development within the urban planning profession over the past 10 years.

However, sustainable development is a recent, controversial concept (Innes J. 2007). Wheeler, in his 2004 book, defines sustainable urban development as "development that improves the long-term social and ecological health of cities and towns." He sketches a 'sustainable' city's features: compact, efficient land use; less automobile use, yet better access; efficient resource use; less pollution and waste; the restoration of natural systems; good housing and living environments; a healthy social ecology; a sustainable economy; community participation and involvement; and preservation of local culture and wisdom (Levy J.M. 2011).

To improve the success of such exercises a number of specific project management techniques have been devised such as Collaborative Strategic Goal Oriented Programming (CoSGOP). This is a collaborative way of strategic planning, decision-making, implementation, and monitoring which is designed around achieving defined and specific goals.

CoSGOP is based on not only the detailed analysis of the available data it relies upon the maximum use of stakeholder consultation to build consensus and hence reduce contention within the project from its initial conception through to its completion.

2.1.5 Collaborative planning in the United States & the UK

Collaborative planning arose in the US and the UK in response to the inadequacy of traditional public participation techniques to provide real opportunities for the public to make decisions affecting their communities.

Collaborative planning is a method designed to empower stakeholders by elevating them to the level of decision-makers through direct engagement and dialogue between stakeholders and public agencies, to solicit ideas, active involvement, and participation in the community planning process. Active public involvement can help planners achieve better outcomes by making them aware of the public's needs and preferences and by using local knowledge to inform projects. When properly administered, collaboration can result in more meaningful participation and better, more creative outcomes to persistent problems than can traditional participation methods. It enables planners to make decisions that reflect community needs and values, it fosters faith in the wisdom and utility of the resulting project, and the community is given a personal stake in its success (LUDA 2010).

Experience shows that successful collaborative planning depends on a number of interrelated factors that involve all the stakeholders (Planners, Government & the Public):

- Inclusivity – all stakeholders must be invited to contribute
- Decision making - the stakeholders have the final decision-making authority
- Government commitment - both financial and technical must be present
- Clear Objectives – the non-technical stakeholders to be given clear objectives by planners
- Expert Opinion – planners provide guidance, consultancy, expert opinions and research
- Conflict – the meeting should be trained in conflict resolution and be in-tune with the needs and wants of all the stakeholders, especially the members of the public affected by the proposed development(s) (Northern Ireland 2006).

3. INTERACTIVE 3D SIMULATION TECHNOLOGY

VR-Design Studio is an example of the latest development in Interactive 3D Simulation and Modeling software technology from Japanese company FORUM8 (Smyth L. 2010).

The company has two development aims for VR-Design Studio: The first being to enable the user to reproduce all aspects of the real world within the software's interactive 3D space. The second is to enable the user to import data from 3rd party industry standard software applications and thereby add significant value to their projects.

VR-Design Studio is a modern solution for urban and transport planning and design projects, either applied on its own or coupled with third-party 3D design / engineering data and /or micro-simulation applications.

The software is also used extensively to plan for and visualize emergency scenarios within roads, buildings and tunnels either involving vehicles or pedestrians or indeed both.

Due to the high visual quality of the software and its high level of interactivity, VR-Design Studio powers a number of different Driving Simulators by many of the world's leading vehicle manufacturing companies and research institutions.

Users of VR-Design Studio can dynamically manipulate 3D space, import and edit 2D & 3D CAD data, build and texture block models, automatically build roads, tunnels & bridges, view multiple design alternatives in real-time, control the weather and overall environment, as well as being able to visualize and edit intelligent traffic in ways previously not possible & much more…

There are many software plug-ins available that enable third party products to benefit from VR-Design Studio's unique interactive visualization capabilities. These include industry standard engineering systems such as Allplan, InRoads & Civil3D as well as pedestrian and emergency evacuation simulation systems such as Legion and EXODUS and popular micro-simulation transport systems such as S-Paramics & Vissim.

CAD & GIS data can be imported in a number of industry standard file formats and there is a plug-in that enables LiDAR point cloud data to be imported directly into VR-Design Studio 3D environments.

A software development kit is also available as well as a 3D VR data creation service.

3.1 Interactive 3D Simulation & the Stakeholder Consultation Process

The traditional way to involve the local community in proposed new highway and other related transport developments was to produce a model of the development (often a physical model) and then invite the public to view it while it was displayed in the local town hall or library.

As time moved on and technology developed, these architectural models became digital. However, due to the complex nature of the 3D software, more often than not all the stakeholders could see were large photographic prints showing various views (architect's impressions), views that obviously showed the development is its 'best light'.

With the development of Interactive 3D Simulation & Modeling software (such as VR-Design Studio) it became possible for urban planners to engage with stakeholders in a totally new and interactive way. For the first time the planners could take their engineering drawings and convert them into highly photorealistic interactive 3D models of the proposed new development quickly and easily.

In the case of a proposed new highway development, not only could you now see the proposed new structure, you could actually simulate traffic and run as many different scenarios as you wish to test the feasibility of the design in virtual space (Ito Y. 2010).

This type of process was adopted by a number of Transportation Authorities, including the Contra Costa Transportation Authority in California. One particular project involved testing people's opinion to the proposed development of new overhead gantries and electronic signage on a 10 mile stretch of the I-80 highway.

This project involved the production of an accurate, photo-realistic 3D interactive model of the I-80 corridor travelling Westbound in Contra Costa County to the Bay Bridge, using Forum8's VR-Design Studio software.

An accurate virtual-reality model of the I-80 corridor was produced, including its street furniture, its existing signage, its surrounding infrastructure and the built environment. In addition the 12 new overhead signage gantries were produced and added to the virtual environment along with other infrastructure items as detailed in the engineering consultancy's preliminary design drawings.

Once built Forum8 activated the virtual 3D environment and populated it with appropriate vehicles. Scripts were set up so that users could drive in both directions on the I-80, either as driver or passengers (by means of low cost steering racks) and thereby assess the visual impact of the proposed signs along the highway. Furthermore, the signs included "live" changeable messages that could be programmed by the user of the Forum8 interactive 3D model.

Fig. 1: Testing Proposed Gantries in Various Weather Conditions

This type of interactive 3D simulation and modeling software can be used as a stakeholder consultation tool in a number of ways. Typically it has been used to produce movies that show before and after scenarios, as in the case of Utah DOT and a proposed flyover to relieve the congestion at an important junction.

This project was located just southwest of Brigham City, Utah, and involved the proposed construction of a new free-left-turn flyover designed to alleviate serious congestion by accommodating the eastbound 1100 South (US-91) traffic that wanted to travel south on I-15.

Though the State recognized that this investment would potentially improve the economic vitality of the community, the project team decided that they needed to open proactive dialogue with the community, land developers and other stakeholders, whilst at the same time exploring alternative lower cost options. They therefore decided to utilize the power of 3D digital visualization and simulation software in the form of VR-Design Studio.

Fig. 2: Utah DOT I-15 / 1100 South Congestion Project

However the software can have a much more powerful effect on the consultation process when its full interactive features are made available to the stakeholders.

For example, when you enable stakeholders, such as local politicians and members of the public to actually drive through the proposed new environment and experience for themselves the effect the proposed new highway development would have on the existing landscape and overall environment.

This new means of interactive stakeholder consultation has been used in many cases recently including by Wisconsin DOT to help members of the public understand more about roundabouts and how to deal with them.

Mark Lenters, the President of Ourston Roundabout Engineering, the company commissioned by Wisconsin DOT to manage the project commented; "In the US roundabouts are still rare and so the average driver often cannot understand how to navigate them or indeed understand the benefits to the transport planner. As anyone knows who has travelled in Europe, roundabouts are a common feature of most road networks and are seen as the ideal solution to relieving congestion at intersections, as well as dealing with intersections that have more than 4 entrances / exits."

Ourston had previously utilized educational videos and pamphlets in attempt to convince the American public that roundabouts are nothing to be afraid of, but neither had been successful.

When Ourston landed the massive project for US41 in Wisconsin, which involved the design of 44 new roundabouts Mark Lenters approached Forum8 and its 3D Visual Interactive Simulation software VR-Design Studio.

Fig. 3: Learning to Drive the Roundabouts in 3D VR Space

VR-Design Studio was able to provide a practical solution whereby the public could drive through the planned roundabouts in 3D virtual space using a USB steering wheel. In this photo-realistic and spatially-accurate environment drivers could understand exactly what their journey to work would be like after these roundabouts were built. In addition the transport planners obtained valuable information regarding the effect these roundabouts would have as they could see them in 3D and in the context of the existing environment.

Mr. Lenters believes that "roadway designers need to take advantage of these new innovative technologies to present the public with the best possible visualization of their proposed projects".

4. THE LATEST DEVELOPMENTS IN INTERACTIVE 3D VR

Although the use of Interactive 3D Simulation & Modeling software like VR-Design Studio provides planners and politicians with an excellent new tool to employ in the stakeholder consultation process, there is still the issue of how do you enable the actual stakeholders to interact with the proposed new environments within the VR space.

As already mentioned the use of photographs and videos on web sites is a useful addition to the process, however if it was possible to enable stakeholders to actually interact with the proposed new development in the VR space and complete questionnaires on-line, wouldn't that improve the whole consultation process enormously.

The way that Forum8 has solved this problem is through the development of VR-Cloud®.

4.1 Cloud Computing

Cloud Computing is set to change the face of Enterprise IT "Cloud Computing is a pay-per-use model for enabling, available, convenient, on-demand network access to a shared pool of configurable computing resources (networks, servers, storage, applications, services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" (Mell P. 2009).

4.1.1 4.1.1 Public Cloud

Forum8's chosen utility cloud service is 'The Digital Planet Public Cloud'. Using this service customers are able to access exactly the cloud based capacity they need, when they need it. Servers and Storage can be scaled up and down by the customer via a customized and dedicated web portal. The customers are then billed monthly based on hourly usage of the selected resources. The Digital Planet Public Cloud is an excellent solution, especially for those customers looking for a way to cost effectively manage their own standard environment, with maximum flexibility and scalability.

VR-Cloud® is a cloud-based 3D Visual Interactive Simulation system that allows anybody to access and interact with a Forum8 3D VR environment via the internet – including via Android smart phones. The product is available in three packaged forms – VR-Cloud® Flash Version; Standard and Collaboration.

VR-Cloud® Flash - Users can host Forum8 3D VR environments on their websites using a Flash player and anybody can access and interact with the 3D environment without having to install any additional software. However, due to the Flash environment, it lacks some of the features available within VR-Design Studio.

VR-Cloud® Standard – This uses a special cloud system developed by FORUM8. It is faster than the Flash version and supports more concurrent users.

VR-Cloud® Collaboration – This is based on the same system as VR-Cloud® Standard, but includes user collaboration features such as 3D bulletin boards and annotations. These features allow the users to annotate within the 3D environment using words and shapes, helping users with their presentations and discussions. VR-Cloud (R) in conjunction with VR-Design Studio is a consensus building solution which uses 3D and VR on a cloud server. With only internet access being required, even a 'thin client' would be able to view and interact with the VR space via a web browser.

VR-Cloud® Flash - This version of the product was first known as SaaS and involves running VR-Design Studio on one or more servers with the remote control of the VR space achieved via Adobe Flash. Although somewhat limited in operation this version does expand public access to VR-Design Studio based Interactive 3D environments.

Potential data publication methods:

- Web free access - The data created in VR-Design Studio is open to the public for viewing and for comment and opinion
- Web seminar / show - It is possible to use the presentation and simulation function of VR-Design Studio to explain and demonstrate the 3D data to a large number of web seminar participants
- Cluster Option - By using the cluster option of VR-Design Studio, all users can share the same VR environment (traffic situation, time, the weather, etc.).

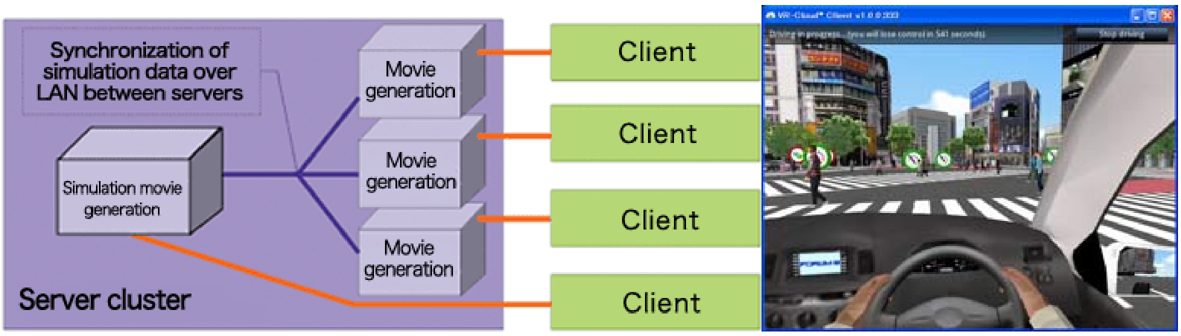


Fig. 4: The VR-Cloud Cluster Operation

As the number of clients that can be supported by one server is restricted, it's possible to combine two or more servers together. It is also possible to synchronize the VR environmental status of the servers by the use of the cluster option.

VR-Cloud(R) Standard - In this version of the software 'original transmission' technology has been implemented "a3S (Anything as a Service)", improving the performance by more than 4 times. Adobe Flash Player has not been used in this newer version. All user interfaces have been developed using OpenGL technology. Many simulation functions of VR-Design Studio are available in this version including manual driving via the keyboard.

As previously mentioned the performance and function of the VR-Cloud(R) Flash Version has been improved within the Standard version. The new transmission technology "a3S" (Anything as a Service) was developed and used to provide a versatile data communication technique between server and client and a management function.

VR-Cloud(R) Collaboration - In addition to the features of the Standard version, the application of advanced VR enabling consensus discussion and feedback on the cloud, such as the 3D bulletin board and annotation functions, etc., are now possible.

- 3D Bulletin Board: as well as the bulletin board and forum on the internet, it's also possible for users to write comments in VR space, create discussions, display items, browse the various discussions and replay other users' comments. The created discussion is displayed on the specified VR space position using a 3D icon. Synchronization between servers is also enabled.
- Annotation: using the simplified editor enables users to produce an annotation, such as a figure or text, etc, within the VR space directly, and then edit it. The created annotation is displayed on a specified position within the VR space and the other users can browse and respond accordingly.

5. CONCLUSION

As discussed in this paper the design and planning of urban and transport infrastructure has undergone a tremendous transformation over the past few years. The adoption by planners of 3D digital representations of proposed new developments, to the exclusion of 2D drawings and photographs, has revolutionized the whole planning process and in particular the way in which stakeholder consultation and consensus building can now take place.

As 3D software technology has developed, so have the requirements of planners, politicians and the general public. The advent of Cloud computing along with interactive 3D simulation and modeling software like VR-Design Studio means that planners can now broadcast their plans on the Cloud to be reviewed and commented on by any stakeholder irrespective of where they are – all they need is web access. This paper highlights these changes and how the latest in interactive 3D Cloud based technology adds a whole new dimension to the stakeholder consultation and consensus building process.

It describes how a new Cloud based product enables stakeholders to not only view the proposed new developments in 3D from their PC or Android, but they can also walk or drive through the 3D space as if they were actually there. In addition, they can also add their comments on-line or answer questionnaires. With the advent of this technology the whole stakeholder consultation process has suddenly moved into the 21st century. It is to be hoped that urban and transport planners around the world embrace it with open arms and thereby help to prevent some of the architectural and planning disasters of the past.

6. ACKNOWLEDGEMENTS

We acknowledge the invaluable contribution of a number of people to this project in particular our colleagues in the development team at FORUM8 and in particular Christophe Soulier and their leader Yoann Pencreach .

7. REFERENCES

Conway G. (2011). *Introduction to Cloud Computing: IVI White Paper.* IVI: Innovation Value Institute, National University of Ireland, Maynooth.

Flyvbjerg, B., Skamris Holm M. K., & Buhl, S. L. (2005). How (in) accurate are demand forecasts in public works projects? Journal of the american planning association, 71 (2), 131-144.

IBMTech Trends Survey. (October, 2010). Published electronically, www-03.ibm.com/press/us/en/pressrelease/32674.wss

Innes J. and Booher D. (2000). Public participation in planning, new strategies for the 21st century, *Working paper 2000-2007*, Institute of Urban and Regional Development, University of California, Berkeley.

Ito Y., Lorentzen T., Hafferty B., Tazawa S. and Goto H. (October 2010), The application of 3D visual interactive drive simulation technology to safer road design, *Presented at the ITS world congress, Busan, South Korea*.

Levy J. M. (2011). *Contemporary Urban Planning*. Boston, Longman.

LUDA project coordination team (2010), Improving the quality of life in large urban distressed areas, *LUDA E-compendium, Handbook E4Annex 1 & Annex,* http://www.ludaproject.net/compendium/pdf/hbe4_annex.pdf

Mell P. and Grance T. (October 2009). Published electronically, *The NIST Definition of Cloud Computing*, Version 15. http://www.nist.gov/itl/cloud/upload/cloud-def-v15.pdf

CASH FLOW OPTIMIZATION AND VISUALIZATION OF RESIDENCE HOUSING FOR BUILDERS

Hong Xian Li, Hexu Liu, Xiangyu Zhou, Chen Sun, Ka Hou Ngan, & Mohamed Al-Hussein
University of Alberta, Edmonton, Canada

ABSTRACT: *Cash flow management is widely considered to be a key issue within the construction industry, especially for residential homebuilders. Cash flow in the residential housing industry involves multiple stakeholders, such as lot developers, banks, clients, trades, and builders; usually the builder initiates a complex plan involving lot procurement, construction investment, and housing sales, which has the potential to lead to more profitable solutions for the builder. This research develops a decision support system subject to variable developer and bank payment schedules, and is based on a twofold objective: (1) Maximize cumulative (negative) cash flows, subject to the guaranteed net present value (NPV) for developers and bank. The optimum solutions help builders to stay within the bank overdraft limit and reduce the pressure of cash demands for builders. (2) Maximize builder's NPV and increase the NPVs of developers and banks as much as possible. With the multi-objective optimization, the win-win optimal solutions serve as negotiation strategies between these stakeholders. The proposed decision making system is highlighted by the application of visualization techniques; two types of visualization techniques, i.e., a combined Excel and add-in and a preliminary Augmented Reality (AR), are utilized to illustrate the optimizing process and the optimal solutions, with the cash inflows, outflows, and the net cash flows for different time periods displayed dynamically. A case study based on a project in Edmonton, Canada is utilized to demonstrate the proposed methodology.*

KEYWORDS: *Cash Flow Management, Cash Flow Optimization, Residential Housing, Builder, Visualization, Decision Support System.*

1. INTRODUCTION

Cash flow management is a vital issue in the construction industry domain, with large amounts of cash flow occurring daily. This issue is imperative, especially for residential homebuilders, since the cash flows of builders involve multiple stakeholders, such as lot developers, banks, clients, and trades. Homebuilders manage cash flows to meet the requirements from different stakeholders, and make profits as well. Usually homebuilders initiate a complex plan involving lot procurement, construction investment, and housing sales; however, initial planning has the potential to lead to more profitable solutions for homebuilders.

The existing literature has addressed various aspects of cash flow management. Peer and Rosental (1982) showed that cash flow management is an indispensable tool for construction companies, where poor cash flow management could lead to company failure due to lack of working capital, even if projects are profitable. The significance of cash flow management has garnered attention from construction managers and researchers, and many studies with respect to cash flow management have been conducted in recent decades. Elazouni and Gab-Allah (2004) examined the effect of balancing the financial requirement with the cash available during the same period using an integer-programming finance-based scheduling method to satisfy the finance availability constraints. Navon (1996) developed an adequate cash-flow management system. With an examination based on the expense flow, income flow, and time lag, Navon raised the idea of creating a mathematical model of cash-flow management for the organizational level, and followed with a computer program written on this basis. More recently, a project-level cash flow forecasting model from the contractor's viewpoint has been introduced (Park et al., 2005). Park et al. mainly focused on a forecasting cash flow model for construction projects, with consideration of both variable cost and time lag, by developing two types of models: a cash-in model and a cash-out model. Lucko (2010) reviewed the literature on financial and project management, and examined how to accurately determine financing fees, particularly interest. This study presented the derivations of financing fees and the logarithmic expressions, which were compared with the approximations from the literatures. In a subsequent study, Lucko (2011) addressed the cash flow optimization from the view of contractors, and proposed an innovative modeling method with singularity functions. Based on a case example, this study modeled cash

Citation: Li, H. X., Liu, H., Zhou, X., Sun, C., Ngan, K. H. & Al-Hussein, M. (2013). Cash flow optimization and visualization of residence housing for builders. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

flow with singularity functions and optimized profits utilizing simulated annealing. In 2008, an investigation based on cash flow for optimization profit in multi-project environments was conducted (Liu et al., 2010). Chen et al. (2010) introduced an ant colony optimization approach for optimizing discounted cash flows. They introduced the notion of using net present value (NPV) to determine the difference between discounted cash inflows and outflows. They also developed several functions in conjunction with various algorithms to maximize the final NPV.

Visualization is another important research area within the construction domain, and generally visualization research can be categorized into virtual reality (VR) and augmented reality (AR). Through the use of visualization technology, construction processes can be visualized before breaking ground and monitored throughout construction. Errors can be detected and monitored through visualization such that the project manager can address them proactively, which reduces construction cost and duration. Due to the advantages of visualization, a considerable amount of research related to construction visualization has been conducted in recent decades, especially with the development of powerful computers. Other researchers have focused on construction operation visualization technology. Al-Hussein (1999) developed a 3D animation for planning crane operations, and used the 3D animation to facilitate crane selection, location, and onsite utilization. Kamat and Martinez (2001) developed a methodology which combined operation simulation and visualization, and described a first version of a general-purpose 3D visualization system that is simulation and CAD software-independent. The visualization contributes to the construction monitoring system when used during construction. For example, a new framework in which productivity and carbon footprint are measured and visualized was proposed by Heydarian and Golparvar-Fard (2011). In 2012, the same research group (Memarzadeh and Golparvar-Fard, 2012) presented a new carbon footprint monitoring tool that enables contractors and managers to reliably and effectively benchmark, monitor, and visualize the expected and released embodied carbon footprint of a construction project. The proposed method is based on a state-of-the-art technology generating multi-dimensional augmented reality models, and the expected and released embodied carbon footprint of a project are both represented in the model.

Although numerous research studies examining either cash flow management or visualization in construction have been conducted, to the authors' knowledge no research has combined the two, and visualization technology has not been utilized in cash flow management. This paper describes the use of visualization in cash flow management in order to supply a more efficient tool for decision making. This paper is organized as follows: first, a quasi-model using Microsoft Excel is presented which is developed to interpret the continuous net cash flow at a time unit of day, based on the forecasting data from a homebuilder in Edmonton, Canada; the further development of the optimization model to minimize the negative cash flow and maximize the homebuilder's NPV is then described. The use of two techniques to visualize the optimization process and optimized cash flow, and a comparison of the two techniques, are then presented.

2. RESEARCH OBJECTIVE AND METHODOLOGY

The aim of this research is to manage and optimize cash flows from the perspective of residential homebuilders, assisting homebuilders to meet the requirements from different stakeholders and to make more profitable plans; meanwhile, this research explores the application of visualization technology for cash flow management and optimization. The research objective is described in greater detail in the following section.

2.1 Research objective

This research is based on the assumption that all capital investments and funds to cover cash deficits are withdrawn from the bank loan, and that the builders have no liquidity. Cash flow optimization and management after the cash flow profiles are streamed constitute the primary objects of this research, and the research objective is twofold:

Objective 1: maximize the minimum cumulative cash flow (negative cash flow) for homebuilders. Cash flow comprises cash inflows and cash outflows, where the construction direct cost, indirect cost, lot payment, and interest are calculated in order to determine the cash outflow, and the bank payment is computed as the only cash inflow. The minimum cumulative cash flow is maximized, subject to bank and developer payment schedules. The maximized minimum cash flow helps builders to stay within the bank credit limit.

Objective 2: maximize the NPV for builders. Subject to the different payment schedules of bank and developers, and the guaranteed NPVs for bank and developers, the builder's NPV is optimized; according to the optimal solution, win-win financial strategies are provided for financial negotiations.

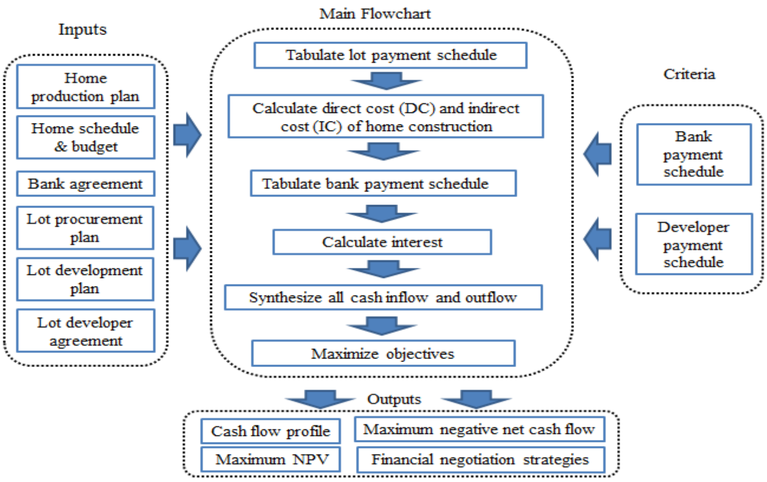
Besides the above research objective, the application of visualization technology for cash flow management and optimization is another aim and of this research.

2.2 Research methodology

A homebuilder's development plan consists of the input information of the research methodology, including house production plan, house construction schedule and budget, lot procurement plan, lot payment schedule, lot developer agreement, and bank agreement. Based on the input information, the cash outflow is calculated, accommodating lot payment, house construction direct cost (DC), indirect cost (IC), and interest. The cash inflow is determined by payments from the bank. By synthesizing the cash inflow and outflow, the cash flow

Fig. 1: Research methodology

profile and the cumulative cash flow profile are streamed accordingly. Subject to variable bank payment



schedule and lot developer payment schedule, two types of optimization are modeled corresponding to two optimization objectives: (1) cash flow profile optimization: the minimum cumulative cash flow is maximized, subject to variable bank and developer payment schedules and guaranteed developer and bank NPVs; this optimization model results in the maximum negative cumulative cash flow, which assists builders to meet the bank overdraft limit; (2) optimization of builder NPV: in this model, multi-objective optimization is applied, where the aim is to maximize the builder's NPV; the NPVs of developers and banks are also increased as much as possible. The optimization process is subject to different bank and developer payment schedules, and the win-win outputs serve as the financial negotiation strategies. The output of the research methodology is twofold corresponding to two research objectives: (1) cash flow profile and maximized minimum cash flow, which relieve homebuilders of cash flow pressure and help homebuilders to stay within bank overdraft limit; (2) maximized NPV for homebuilders, and win-win financial negotiation strategies, which benefit homebuilders, the bank, and developers. The research methodology is summarized in Figure 1, and the optimizations are modeled as Equations (1) to (13).

.

2.2.1 Cumulative cash flow profile and optimization

$$Max.\left(Min(CC_t)\right) \tag{1}$$

$$s.t.$$

$$CI_t = BP_t \tag{2}$$

$$CO_t = LP_t + DC_t + IC_t + I_t \tag{3}$$

$$NC_t = CI_t - CO_t \tag{4}$$

$$I_t = NC_{t-1} \times i \tag{5}$$

$$CC_t = CC_{t-1} + NC_t \tag{6}$$

$$NVP_B = \sum_{t=0}^{N} \frac{BP_t}{(1+i)^t} = NPV_{B0} \tag{7}$$

$$NVP_{Dj} = \sum_{t=0}^{N} \frac{LP_{jt}}{(1+i)^t} = NPV_{D0} \tag{8}$$

Where CI_t is the cash inflow at time t, CO_t is the cash outflow at time t, NC_t is the net cash flow at time t, CC_t is the cumulative net cash flow at time t, BP_t is the bank payment at time t, LP_t is the lot payment at time t, DC_t is the direct construction cost at time t, IC_t is the indirect construction cost at time t, I_t is the interest at time t, i is the interest rate, NVP_B is the net present value for the bank, and NVP_{Dj} is the net present value for developer j.

2.2.2 NPV optimization for homebuilders

$$Max.(NVP) = Max.\left(\sum_{t=0}^{N} \frac{NC_t(LP_t, BP_t)}{(1+i)^t}\right) \tag{9}$$

$$s.t.$$

$$CI_t = BP_t \tag{10}$$

$$CO_t = LP_t + DC_t + IC_t + I_t \tag{11}$$

$$NC_t = CI_t - CO_t \tag{12}$$

$$NVP_B = \sum_{t=0}^{N} \frac{BP_t}{(1+i)^t} \geq NPV_{B0} \tag{13}$$

$$NVP_{Dj} = \sum_{t=0}^{N} \frac{LP_{jt}}{(1+i)^t} \geq NPV_{D0} \tag{14}$$

Where: NPV is the net present value of the builder, CI_t is the cash inflow at time t, CO_t is the cash outflow at time t, NC_t is the net cash flow at time t, BP_t is the bank payment at time t, LP_t is the lot payment at time t, DC_t is the direct construction cost at time t, IC_t is the indirect construction cost at time t, I_t is the interest at time t, i is the discount rate, NVP_B is the net present value for the bank, and NVP_{Dj} is the net present value for developer j.

2.2.3 Cash flow visualization

As in other areas of construction research, the application of visualization technology promotes the presenting of research and the results. By utilizing visualization techniques, the cash flow management and optimization process can be highlighted and demonstrated dynamically. In our research, two types of visualization technique are utilized and compared. (1) Combined Excel and add-in: by applying integrated simulation and optimization software, i.e., OptQuest in Crystal Ball, the optimization process can be visualized with the values of cells changed dynamically. Furthermore, in this paper, the integrated simulation and optimization are combined with the graph-generating technique in Excel, and the cash flow profiles are visualized dynamically during the optimization process. (2) Preliminary Augmented Reality (AR) technique: A preliminary AR is utilized to demonstrate the optimal cash flow scenario on a predefined image. The application of AR highlights the presenting of the optimal cash flows with a dynamic tool and predefined building information (image).

3. CASE EXAMPLE

A builder in Edmonton, Canada provided the following cash flow information: (1) House production plan data for the time period between August of 2013 and June of 2015: the detailed information includes house job number; predicted contract date between the builder and the home owner; construction start date, allowing for a lag of 60 days for pre-construction stage; and estimated home price and cost (excluding lot cost). (2) House cost-schedule integrated data: this includes all houses listed in the production plan, with cost and schedule broken down to the purchase order level (construction tasks). (3) Bank agreement data: this lists the bank payment schedule as agreed upon with the builder; the bank payment schedule is presented using bank payment milestones with specific descriptions as in Table 1. In this research, it is assumed that the builder deals with one bank only and there are six milestones for bank payments, each with a corresponding payment percentage. (4) Developer agreement data: this data assigns the payment schedule to the developers as stated in the contract between the developer and the builders. The developer payment schedules are presented using developer payment schedules as in Table 2; in this research, there are three lot developers who deal with the builder, and there are eleven milestones for each developer payment, each with a corresponding payment percentage. (5) Lot procurement plan: this plan lists the predicted lots to be purchased and their respective prices, expected developers, and purchasing dates. An annual interest rate of 4% is adopted in this research. The building phases, including development phase, construction phase, and possession phase; developer payment milestone; and bank payment milestone are illustrated in Figure 2.

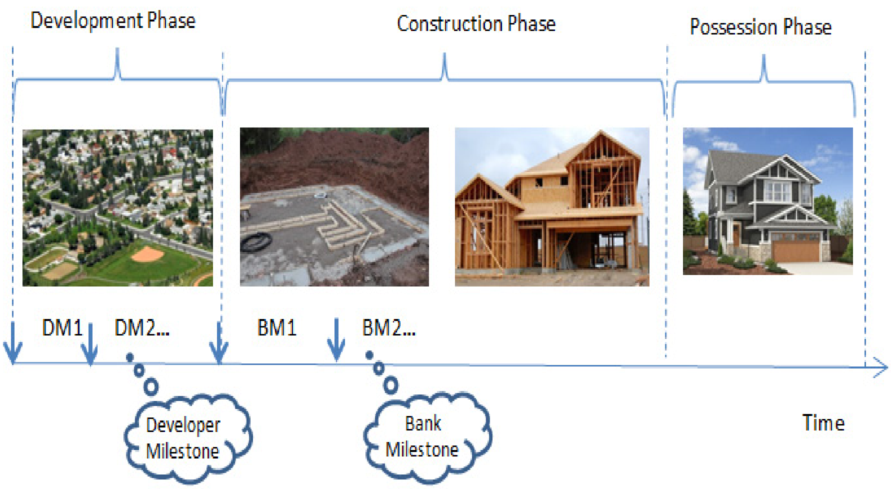


Fig. 2: Building Phase and Milestone.

Table 1: Original Bank Payment Schedule.

Payment Milestone	Description	Percentage of Home Price
1	Sign contract	5%
2	Start Construction	0%
3	Stake out	27%
4	Painting	25%
5	Possession date	33%
6	Lean hold back release	10%

Table 2: Original Developer Payment Schedule.

Developer 1	Payment Milestone	1D1	1D2	1D3	1D4	1D5	1D6	1D7	1D8	1D9	1D10	1D11
	Payment Percentage	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	0%
Developer 2	Payment Milestone	2D1	2D2	2D3	2D4	2D5	2D6	2D7	2D8	2D9	2D10	2D11
	Payment Percentage	5%	0%	25%	0%	25%	0%	0%	45%	0%	0%	0%
Developer 3	Payment Milestone	3D1	3D2	3D3	3D4	3D5	3D6	3D7	3D8	3D9	3D10	3D11
	Payment Percentage	20%	0%	0%	20%	0%	20%	0%	20%	0%	0%	20%

3.1 Cash flow profile

With the input data retrieved and sorted, the cash inflows and outflows are calculated in daily units. After synthesizing the cash inflows and outflows, the original net cash flow profile and cumulative cash flow profile are generated, as shown in Figure 3. The original minimum cumulative cash flow is determined to be -$5,998,747.

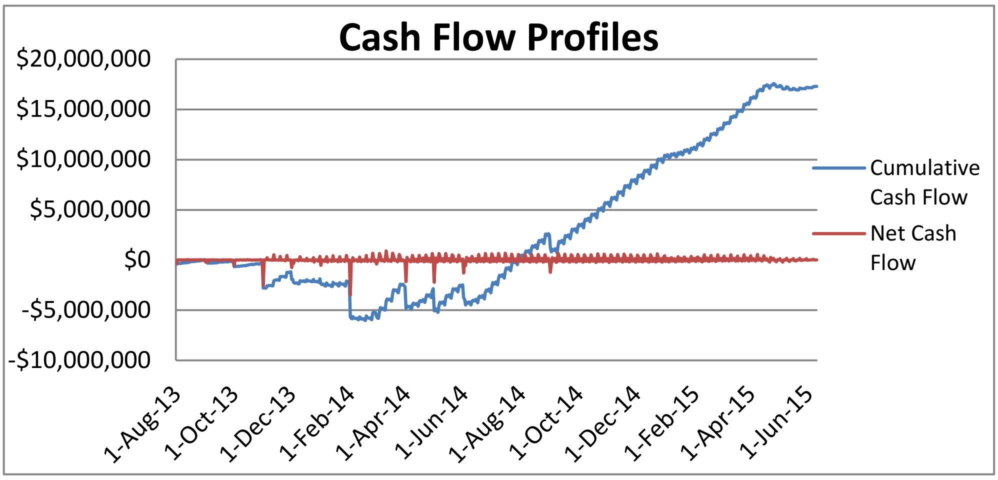


Fig. 3: Cash Flow Profile.

3.2 Minimum cumulative cash flow optimization

In order to assist the builder to stay within the bank overdraft limit, the minimum cumulative cash flow (negative cash flow), which is subject to the variable payment schedules and the guaranteed NPVs of developers and bank, is maximized. The cash flow profile optimization model (Equation (1) to (8)) is applied for this case; the maximized negative cumulative cash flow is $200,142, and the optimal solutions are as presented in Tables 3 and 4 and Figure 4. In this case, Microsoft Excel Solver is utilized as the optimization tool, since OptQuest cannot find a feasible solution for the fixed constraint requirements of this model.

Table 3: Optimal Bank Payment Schedule for Maximized Negative Cumulative Cash Flow.

Payment Milestone	Description	Percentage of Home Price
1	Sign contract	53%
2	Start Construction	0%
3	Stake out	0%
4	Painting	0%
5	Possession date	0%
6	Lean hold back release	47%

Table 4: Optimal Developer Payment Schedule for Maximized Negative Cumulative Cash Flow.

Developer 1	Payment Milestone	1D1	1D2	1D3	1D4	1D5	1D6	1D7	1D8	1D9	1D10	1D11
	Payment Percentage	0%	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Developer 2	Payment Milestone	2D1	2D2	2D3	2D4	2D5	2D6	2D7	2D8	2D9	2D10	2D11
	Payment Percentage	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	82%
Developer 3	Payment Milestone	3D1	3D2	3D3	3D4	3D5	3D6	3D7	3D8	3D9	3D10	3D11
	Payment Percentage	42%	0%	0%	0%	0%	0%	0%	0%	40%	0%	18%

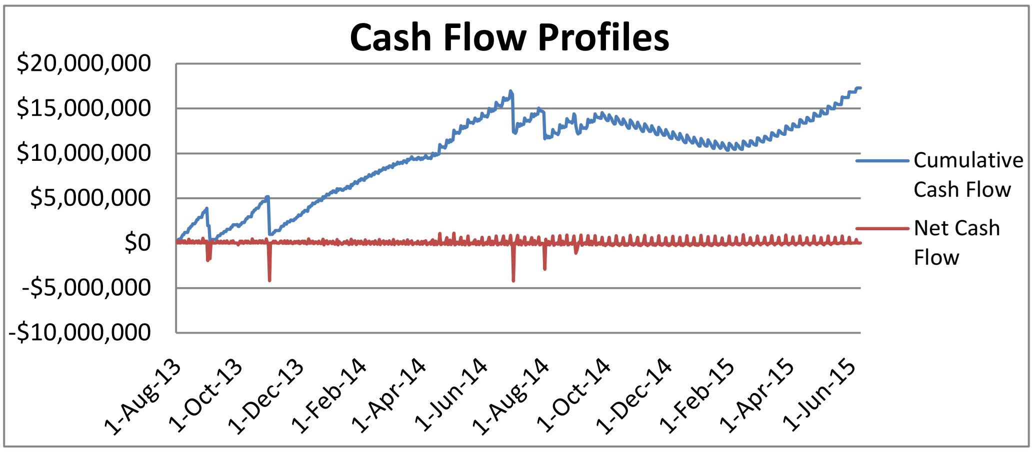


Fig. 4: Optimized Cash Flow Profile I.

3.3 NPV optimization

The building plan initiated by the builder is not the optimal solution, and has the potential to make more profits for the builder, the bank, and the developers through multi-objective optimization. In order to improve the profitable solutions, the NPV optimization model (see Equations (9) to (13)) is applied, with the builders' NPV maximized. The NPVs of the developers and the bank are also increased as much as possible. The optimizing tool, OptQuest, is utilized for this case, generating optimization solutions which provide win-win strategies for the stakeholders; at the same time, the optimization process is visualized. The builder's NPV increases from the original value of

$14,446,134 to the maximum value of $15,838,977. The optimal solutions are summarized in Tables 5 and 6 and Figure 5.

Table 5: Optimal Bank Payment Schedule for Maximized Builder's NPV.

Payment Milestone	Description	Percentage of Home Price
1	Sign contract	100%
2	Start Construction	0%
3	Stake out	0%
4	Painting	0%
5	Possession date	0%
6	Lean hold back release	0%

Table 6: Optimal Developer Payment Schedule for Maximized Builder's NPV.

Developer 1	Payment Milestone	1D1	1D2	1D3	1D4	1D5	1D6	1D7	1D8	1D9	1D10	1D11
	Payment Percentage	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%
Developer 2	Payment Milestone	2D1	2D2	2D3	2D4	2D5	2D6	2D7	2D8	2D9	2D10	2D11
	Payment Percentage	0%	0%	0%	100%	0%	0%	0%	0%	0%	0%	0%
Developer 3	Payment Milestone	3D1	3D2	3D3	3D4	3D5	3D6	3D7	3D8	3D9	3D10	3D11
	Payment Percentage	100%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

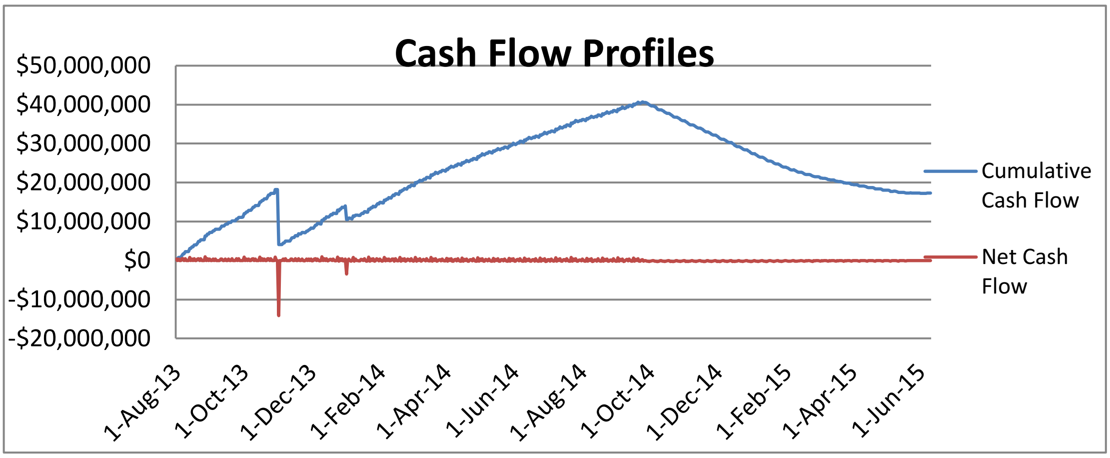


Fig. 5: Optimized Cash Flow Profile II.

3.4 Cash flow and optimization visualization

Two visualization techniques are applied in this research:

1) Optimization process visualization:

This research applies an integrated simulation and optimization software, i.e., OptQuest in Crystal Ball, which promotes the cash flow optimization visualization; the values in cells are changed dynamically along with the simulation and optimization process. Furthermore, in this research, the cash flow profiles are connected with the changeable cells, resulting in a dynamic cash flow profiles. The combination of the application of software and the dynamic cash flow profile generating technique provides an impressive and dynamic visualization of cash flow optimization. The combined interface of OptQuest and Excel is shown in Figure 6; the performance chart of OptQuest is demonstrated in Figure 7, in which the vertical axis presents the value of the objective function and the horizontal axis displays the simulation generation.

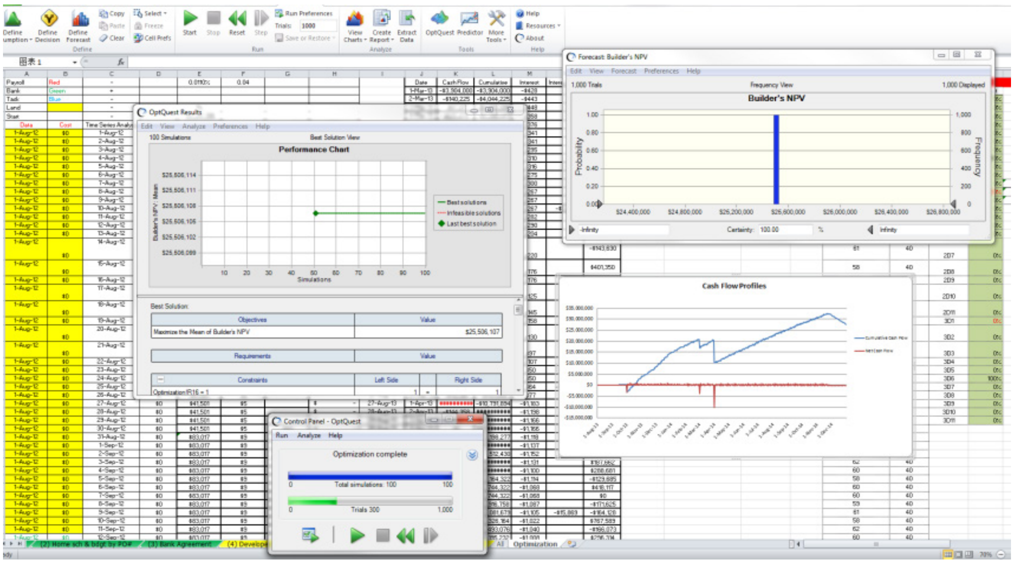


Fig. 6: Combined interface (OptQuest and Excel).

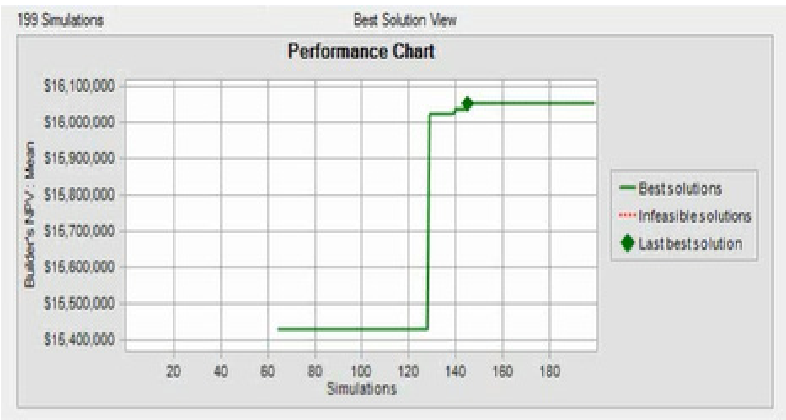


Fig. 7: Performance chart of OptQuest.

2) Best-case scenario demonstration:

A preliminary AR is utilized in this research to demonstrate the optimal cash flow solutions, connected with a predefined image. A snapshot of the optimal solutions is shown in Figure 8, in which the optimal cash inflows and outflows are demonstrated on the cash flow chart, with the cash barrel displaying the net cash flows. The background is a predefined image of a house. A snapshot of a pure animation of the optimal solution is displayed in Figure 9.

Fig. 8: A snapshot of AR.

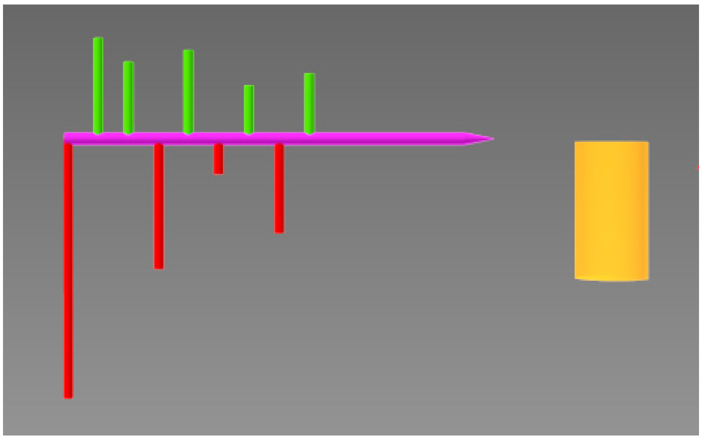


Fig. 9: A snapshot of animation.

4. CONCLUSION

This research addresses two important issues related to cash flow management for residential builders: (1) Minimum cumulative cash flow optimization: subject to variable payment schedules and guaranteed NPVs for developers and bank, the builder's minimum cumulative cash flow has been optimized. The minimum cumulative cash flow is related to the amount of overdraft from the bank, and the optimization helps the builder to satisfy the bank's overdraft limit. (2) NPV optimization: as an important index related to net benefit, the builder's NPV has been optimized subject to variable developer and bank payment schedules; the NPVs of developers and the bank have also been increased as much as possible, i.e., multi-object optimization has been applied to address this issue. Using a case study in Edmonton, Canada, this research has demonstrated that, through the optimizations, the minimum cumulative cash flow improved significantly from -$5,820,855 to $200,142. Also, the NPV of the builder increased from $14,446,134 to $15,838,977, and the NPVs of all of the developers and the bank increased. The optimal solutions alleviate the pressure of cash demands for the builder, and the optimized solutions provide win-win strategies for financial negotiations. During the optimization, two different visualization techniques have been applied to dynamically illustrate the optimizing process and the optimal solutions. With the application of OptQuest the optimization process has been visualized, focusing on the potential solutions and the optimization process. Meanwhile, by utilizing a preliminary AR, the best-case scenario has been demonstrated dynamically. The application of visualization technology has been shown to promote cash flow management and optimization.

5. REFERENCES

Al-Hussein, M., Alkass, S. and Moselhi, O. (1999). 3-D animation for planning crane operations. *Proceedings of 16th IAARC/IFAC/IEEE international symposium on automation and robotics in construction*, Madrid, Spain,151-156.

Chen, W.-N., Zhang, J., Chung, H. H.-C., Huang, R.-Z., and Liu, O. (2010). Optimizing discounted cash flows in project scheduling: An ant colony optimization approach. *IEEE transactions on systems, man and cyberentics - part C: applications and reviews*, Vol. 40, No. 1, 64-77.

Elazouni, A.M. and Gab-Allah, A.A. (2004). Finance-based scheduling of construction projects using integer programming. *Journal of construction engineering and management*, Vol. 130, No.1, 15-24.

Heydarian, A. and Golparvar-Fard, M. (2011). A visual monitoring framework for integrated productivity and carbon footprint control of construction operations. *Proceedings of the 2011 ASCE international workshop on computing in civil engineering* (Yimin Zhu and R.Raymond Issa, editors), Miami, Florida, 504-511.

Kamat, V. R. and Martinez, J. C. (2001). Visualizing simulated construction operations in 3D. *Journal of computing in civil engineering*, Vol. 15, No. 4, 329-337.

Liu, S. and Wang, C. (2010). Profit optimization for multiproject scheduling problems considering cash flow. *Journal of construction engineering and management*, Vol. 136, No. 12, 1268-1278.

Lucko, G. (2011). Optimizing cash flows for linear schedules modeled with singularity functions by simulated annealing. *Journal of construction engineering and management*, Vol. 137, No. 7, 523-535.

Lucko, G and Thompson R. (2010). Derivation and assessment of interest in cash flow calculation for time-cost optimizations in construction project management. *Proceedings of the 2010 Winter simulation conference* (B. Johansson, S. Jain, J. Montoya-Torres, J. Hugan, and E. Yücesan, editors), Baltimore, Maryland, 3037-3048.

Memarzadeh, M. and Golparvar-Fard, M. (2012). Monitoring and visualization of building construction embodied carbon footprint using DnAR - N-dimensional augmented reality models. *Proceedings of construction research congress* (Cai H., Kandil A., Hastak M., and Dunston P. S., editors), Purdue University, 1330-1339.

Navon, R. (1996). Company-level cash-flow management. *Journal of construction engineering and management*, Vol. 122, No.1, 22-29.

Park, H. K., Han, S. H., and Jeffrey S. Russell. (2005). Cash flow forecasting model for general contractors using moving weights of cost categories. *Journal of management in engineering*, Vol. 21, No. 4, 164-172.

Peer, S. and Rosental, H. (1982). *Development of cost flow model for industrialized housing.* Haifa, Israel: Nat. Build. Res. Station.

PART II: BIM AND VR: FACILITY MANAGEMENT APPLICATIONS

EXPERIENCES OF IMPLEMENTING BIM IN SKANSKA FACILITIES MANAGEMENT

Medina Jordan & Howard Jeffrey
Skanska

ABSTRACT

The benefits of BIM (Building Information Modeling) in design, construction and facilities management (FM) are well documented. However, the adoption of BIM in the construction sector is slow, with BIM implementation in facilities services lagging even further behind. Several reasons have been offered for the slow uptake of BIM, such as issues with IT interoperability, lack of understanding of BIM and variable expectations of the system. Difficulties with clearly articulating FM BIM requirements and the inevitable changes to long-established work processes could be the key to the slow progress of BIM in facilities management. Detailed case-studies of BIM implementation in UK FM organisations are not forthcoming.

The facilities management team at Skanska has embraced BIM and this paper describes the challenges the team faced when it prepared the business for a 'BIM way of working', and some early benefits achieved from the fledgling BIM implementation. The paper highlights the importance of clarifying BIM aspirations and identifying and understanding information requirements before focusing on technology, and the importance of only selecting information that can be beneficially utilised. Once information requirements are agreed, identifying when in the building lifecycle the information should be made available requires careful consideration. These timing decisions require close collaboration with and an understanding of other participants, particularly in the design process.

The paper highlights the need to review existing work processes and the time dedicated to the task should not be underestimated. The paper also describes the inevitability of having to change existing work processes (not just in the FM team), the associated challenges and how these challenges were approached by the Skanska facilities Services team.

One of the benefits of BIM that is difficult to quantify is this greater co-operative approach and reciprocal understanding of each stakeholder's needs and constraints. Engaging with people first, adapting existing processes and then using IT systems intelligently are the keys to successful BIM implementation.

KEYWORDS: *BIM; Building Information Modeling; Standards; Data; Information; Implementation; Benefits.*

1. INTRODUCTION

The benefits of BIM (Building Information Modeling) in infrastructure design and construction are well documented, and in recent years, the potential wide-ranging benefits of BIM in facilities management (FM) have also been identified. Frameworks have been proposed for the consideration of FM during the design stages of projects (Wang *et al.,* 2013), and for the quality of handover data to operational teams (Whyte *et al.,* 2012). Teicholz (2013) offers some guidance on how to implement BIM in facilities management and highlights the importance of understanding the goals of linking BIM to FM before commencing with a BIM implementation. Arayici *et al.* (2012) discusses some of the challenges of implementing BIM in FM organisations such as IT interoperability issues, and the maintenance of BIM models during the operational phase to ensure models continue to be fit-for-purpose in supporting FM activities.

However, despite knowledge about BIM and its potential benefits, adoption of BIM in the construction sector has been surprisingly slow, with the application of BIM in facilities management lagging even further behind. Lindblad (2013) proposes various reasons why BIM uptake has been sluggish, citing reasons such as BIM tool interoperability and user knowledge and expectations. The author also raises a very important point about BIM implementation: 'The adoption of BIM is not only a change in technology; there is a need for substantial changes in work processes in order to make improvements to productivity'.

Citation: Jordan, M. & Jeffrey, H. (2013). Experiences of implementing BIM in Skanska facilities management. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Detailed accounts of BIM implementations in UK FM organisations are not forthcoming. Perhaps difficulties identifying how BIM can support FM activities, plus problems changing existing work practices are two of the obstacles that prevent widespread adoption of BIM in the facilities management sector.

This paper gives a first-hand account of the experiences of Skanska's facilities management division when it prepared the foundations for a 'BIM way of working' in the business. Focusing on the 'information' aspect of BIM, this paper highlights the time spent defining how BIM could potentially support day-to-day FM activities, identifying information requirements to enable the efficient transition from the 'as-built' phase to the operations phase, and the challenges faced when changes to existing work practices were required, both within the facilities management and the design and construct teams. The paper also highlights the benefits achieved so far with the fledgling BIM implementation.

1.1 Skanska

Skanska is a well-known construction and development company, with business units around the globe. Its UK division has operations in building, civil engineering, utilities, infrastructure services, piling, mechanical and electrical services, and facilities management.

In response to contractual requirements of private finance initiatives (PFIs), a facilities management function was initially created in Skanska UK's M&E operating unit. By 2008, the FM function became an operating unit in its own right and was called Skanska Facilities Services (FS). The operating unit employs approximately 650 operational and managerial staff. It provides technical building services in the healthcare, defence, education and commercial business sectors throughout the UK. In healthcare, FS manages the 'hard facilities management' for high profile PFI contracts such as St Bartholomew's and The Royal London Hospitals.

In 2008 Skanska's Chief Executive announced that Skanska would implement BIM on all new contracts where Skanska had an influence over building, civil engineering and infrastructure designs. The mandate was effective from 2009 and applied to all Skanska business units around the world. At the time there was no clear definition of BIM, or how or to what extent BIM should be implemented. It was left to each business unit to identify the most effective ways of implementing BIM that best suited their business needs.

A Skanska BIM Council, BIM Forum and BIM Expert Group were established to ensure best practice and knowledge sharing between countries. Roles such as BIM implementation managers, BIM champions and BIM coordinators were also created to translate the edict into practical management and implementation in the businesses.

2. BIM AS A CATALYST FOR PROCESS IMPROVEMENT

At the time of the mandate in 2008, Skanska Facilities Services had little understanding of BIM but it recognised the potential benefits of improved collaborative processes a nd operational efficiencies. The new BIM mandate meant FS would have to identify specific areas where BIM could improve efficiencies, and it was accepted that current operational procedures would have to be reviewed and new methods and technologies would need to be introduced. When early consideration of BIM principles was discussed with managers across the business, variations and deficiencies in operational processes across projects became apparent (see Fig. 1). If Skanska's facilities services team was to properly implement BIM, it would first have to rationalise and standardise key processes throughout the business.

3. ARTICULATION OF BIM REQUIREMENTS

To understand how BIM could be used by the business, FS first had to understand the information needed to help it:

a) Mobilize its O & M (operate and maintain) contracts more efficiently

b) Improve its operational activities (e.g. asset management)

c) Provide building performance information to designers to help them design new buildings with enhanced levels of sustainability

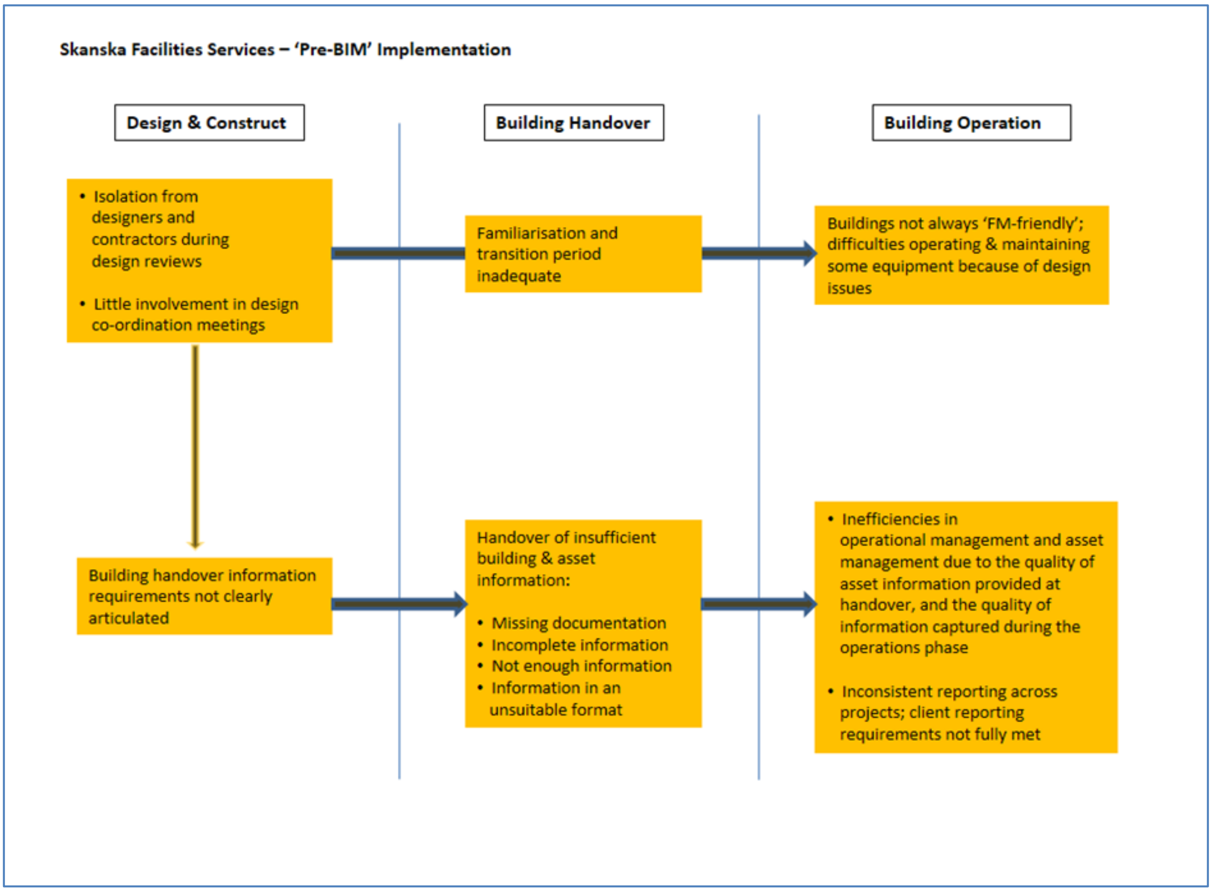


Fig. 1: 'Pre-BIM' process deficiencies

The aspirations were relatively easy to define. What proved more challenging was how to translate these aspirations into practical requirements that could be understood and agreed upon throughout the business. The next challenge was establishing how to articulate these requirements in a format that could be understood and accepted by other stakeholders involved in the design and construction process. This was important as these stakeholders were (and still are) addressing their own challenges around the adoption of BIM. The work done by the facilities services team to improve their own internal processes has certainly impacted upon the deliberations and adoption of BIM by the other stakeholders.

Two projects were undertaken to establish FS' BIM requirements:

- A data & information management project to establish requirements to help improve the transition of building projects from construction to operation, and to improve operational/asset management activities after projects transition to the operate and maintain stage
- An IT improvement project to overhaul the existing IT platform in the business to accommodate the new data and information requirements, and to create a robust IT architecture on which new BIM technologies can be easily integrated

The success of these projects depended on continuous support from senior management in the business – this is an essential element in the development of a 'BIM-friendly' environment.

One of the key issues raised during deliberations about BIM was the timing of the input of FM requirements into the design process (to ensure facilities management was properly considered in the building design). Stakeholders like FS who had traditionally participated in the latter stages of a building project, would now have to articulate their requirements (and have a more influential role) in the early stages of the project. This earlier engagement would result in closer collaborations (particularly with the designers of mechanical and electrical services) and more in-depth discussions about building system requirements would ensue. There would also be earlier provision of information requirements. On Skanska's Woodlands School contract[2] for example, the mechanical and electrical team were given early access to FS' information standards (e.g. asset register template, asset categorization and coding systems) to ensure information supplied to FS at handover would be in the correct format for the smoother commencement of FM activities.

4. BIM AND THE GOVERNMENT CONSTRUCTION STRATEGY

In May 2011 the Government Construction Strategy was launched which specified that all publically procured projects would achieve 'Level 2' BIM by 2016.

The implementation of BIM is not particularly prescriptive and the 'how' (to implement BIM) is currently being defined with assistance from the Government BIM task Group. The proposed protocols include PAS 1192-2 2013 *'Specification for information management for the capital/delivery phase of construction projects using building information modeling'.*

The Government is strongly recommending PAS 1192-2 but it is not mandating it. The relevant clause under the heading: "Fundamental principles for Level 2 information modeling" in PAS 1192-2 is:

> *"e) provision of a single environment to store shared asset data and information, accessible to all individuals who are required to produce, use and maintain it – see Clause **9**;*
>
> *Construction Operations Building Information Exchange (COBie) is a requirement of PAS 1192 -2:*
>
> ***NOTE 2** One of the key Level 2 requirements is the exchange standard of COBie and PDF, as well as copies of the native files."*

Another document that is likely to be relevant (and is currently under development) is PAS 1192-3 (FM standards).

5. PRACTICAL INTERPRETATION OF GOVERNMENT BIM PROTOCOLS

Skanska has had to interpret the PAS 1192-2 protocol and translate it into a process flow chart which identifies the roles and responsibilities for the production of information and management of the process. The flow chart helped to identify where standard protocols exist. Where gaps were found, Skanska has had to fill these with its own protocols and standards.

Each Skanska project now starts with a BIM Project Directive which effectively directs the project to adopt PAS 1192-2 as the basis for BIM delivery. We currently have projects piloting the development of BIM Execution Plans, COBie drops and other recommendations of PAS 1192-2. We are aligning our BIM strategy, which was in development prior to the release of the Government Construction Strategy. This work will inform the process and identify the challenges with the implementation of the so far generally untested government protocols and recommendations.

6. MAIN CHALLENGES IN THE PREPARATION AND IMPLEMENTATION OF BIM IN SKANSKA FACILITIES SERVICES

In our work to prepare the business for BIM, we found that the proportion of effort was approximately 70% people, 20% process and 10% technology.

We had to be clear about our aspirations for BIM and understand our requirements (particularly in the form of information) that would help us achieve those aspirations. This resulted in in-depth studies of existing work

[2] Woodlands School is a £26 million Skanska design, build and operate contract, with Skanska Facilities Services providing FM services from 2014.

processes and gap-analyses of information that was being produced. Once it was clear what was needed for a successful BIM implementation, it was crucial to develop a BIM implementation plan.

Core IT systems used by the business had to be upgraded to complement the new information standards and to enable integration of BIM technologies. This was a fairly straightforward exercise on new projects that had just entered the mobilization phase; retrospective upgrades of existing IT systems on established projects proved more complex.

Support and ongoing leadership from senior management is crucial to successful BIM implementation in the business. We had to develop strategies to communicate the benefits of BIM among the 650-strong workforce in a manner that would engage and maintain their interest in BIM. Key influencers in the business were also identified and they became local BIM champions after they were convinced of the potential benefits of BIM. When changes to existing work processes were required, we had to communicate these changes to the workforce in a manner that persuaded them that the changes would improve their personal way of working. Some changes to design and construction work processes were also needed; closer engagement with these teams has resulted in a better understanding of our operational processes and an appreciation of our new information requirements. The issue of credible material (i.e. new information standards) to these stakeholders was essential before they would commit to altering their existing work processes.

7. BENEFITS OF BIM REALISED SO FAR

Figure 2 illustrates the anticipated benefits of BIM. BIM implementation in Skanska Facilities Services is still in its early stages, but already the business is seeing benefits.

The data & information management project produced a suite of new standards which have been implemented on all new operate and maintain contracts since 2011. An FM BIM requirements protocol was also created for use on all new projects where BIM is used. The IT project resulted in the standardization of a core business IT package (CAFM3) and an upgrade of the IT platform to accommodate future BIM technologies.

Anecdotal evidence indicates that since 2011, mobilization of new operate and maintain contracts have been quicker and smoother, and this been attributed to the implementation of the new data and information standards and the new standard configuration of CAFM systems. One example of improved mobilization is the import of asset registers into the CAFM system which is now done in-house rather than by a third party supplier, saving time and cost. Application of the standards has also resulted in an improvement in the quality of operational data captured by the FM teams following mobilization of the contract.

The organization's FM data & information requirements were incorporated in BIM models that were developed for the Woodlands School project. Earlier involvement on the project has resulted in better understanding and teamwork between FS and the mechanical and electrical services team. Some information best-practices have also been shared among teams. Engagement between FS and the design and construction teams has been very positive on projects where BIM is applied.

Quantifiable benefits achieved so far include:

- Savings in third-party costs for CAFM set-up: since 2013, all aspects of CAFM implementation are managed in-house, with anticipated savings in the region of 1-3% (of annual contract value) on each new FM contract.

- Reductions in staff training time and costs – staff already trained on the company's standard CAFM system can be quickly deployed on new contracts, with little (if any) additional training. Since 2011, typically 5 days' training (per member of staff deployed) has been saved on new contracts, with cost savings in the region of 0.5% (of annual contract value).

---

[3] CAFM – Computer Aided Facilities Management: an IT application used to manage FM operational activities.

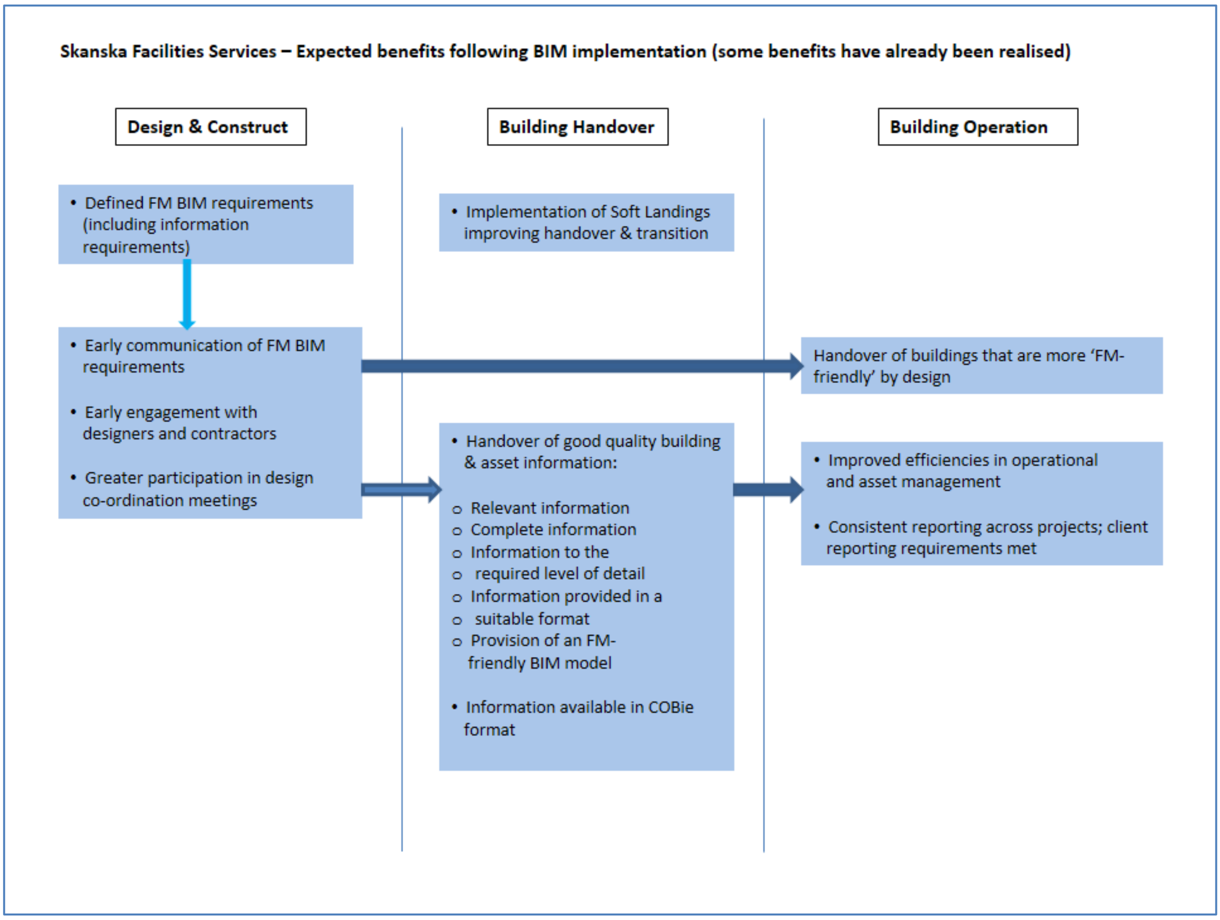


Fig. 2: Anticipated and experienced benefits of BIM implementation

8. CONCLUSION

Skanska Facilities Services invested a lot of time to prepare a robust platform for successful BIM implementation. As the business continues to learn more about BIM, we acknowledge that further work is required to ensure we can fully exploit the benefits of the system.

Successful BIM implementation depends on having a strong implementation strategy, together with continuous support from senior management, and ongoing and evolving communications with all stakeholders.

A robust BIM implementation strategy can only be developed when there is:

- A clear understanding of how BIM can benefit the business
- A clear articulation of BIM aspirations
- Clear definition of BIM information requirements needed to achieve the aspirations
- A clear explanation of what needs to be done to implement BIM on projects.

Inevitably, some existing work processes will have to be modified to accommodate a 'BIM way of working' and some resistance to change should be expected. To mitigate this, 'BIM implementation wins' should be achieved as quickly as possible and communicated effectively to stakeholders. Sustained engagement with stakeholders throughout the entire BIM implementation process cannot be over-emphasised.

9. REFERENCES

Arayici, Y., Onyenobi, T., Egbu, C. (2012). Building information modeling (BIM) for facilities management (FM): The MediaCity case study approach. *International Journal of 3-D Information Modeling (IJ3DIM)* **1**(1): 55-73.

Lindblad, H. (2013). Research paper: Study of the implementation process of BIM in construction projects. Analysis of barriers limiting BIM adoption in the AEC industry. *Thesis no. 263. Department of Real Estate and Construction Management. KTH Architecture and the Built Environment, Stockholm.*

Teicholz, P. (2013). Owner BIM for FM guidelines. *BIM for Facility Managers (2013). IFMA: John Wiley & Sons.*

Wang, Y., Wang, X., Wang, J., Yung, P., Guo, J. (2013). Engagement of facilities management in design stage through BIM: Framework and a case study. *Advances in Civil Engineering* 2013. http://dx.doi.org/10.1155/2013/189105.

Whyte, J., Lindkvist, C., Hassan Ibrahim, N. (2012). From projects into operations: lessons for data handover. *Proceedings of the Institution of Civil Engineers: Management Procurement and Law* 2012.

A WEB3D ENABLED INFORMATION INTEGRATION FRAMEWORK FOR FACILITY MANAGEMENT

Edvinas Rasys, Michael Hodds, Nashwan Dawood & Mohamad Kassem
Centre for Construction Innovation & Research, Teesside University, UK

ABSTRACT: *Managing capital oil and gas and civil engineering facilities requires a large amount of heterogeneous information that is generated by different project stakeholders across the facility lifecycle phases and stored in various databases and technical documents. The amount of information reaches its peak during the commissioning and handover phases when the project is handed over to the operator. The operational phase of facilities spans multiple decades and the way facilities are used and maintained have a huge impact on costs, environment, productivity, and health and safety. Thus, the client and the operator bear most of the additional costs associated with incomplete, incorrect or not immediately usable information.*

Web applications can provide a quick and convenient access to information regardless of user location. However, the integration and delivery of engineering information, including 3D content, over the Web is still at its infancy and is affected by numerous technical (i.e. data and tools) and procedural (i.e. process and people) challenges. This paper addresses the technical issues and proposes a WEB3D-enabled information integration framework that delivers engineering information together with 3D content without any plug-ins. In the proposed framework, a class library defines the engineering data requirements and a semi-structured database provides means to integrate heterogeneous technical asset information. This framework also enables separating the 3D model content into fragments, storing them together with the digital assets and delivering to the client browser on demand. Such framework partially alleviates the current limitations of the JavaScript based 3D content delivery such as application speed and latency. Hence, the proposed framework is particularly valuable to petroleum and civil engineering companies working with large amounts of data.

KEYWORDS: *Information integration, Facility Management, Class Library, Web3D, WebGL*

1. INTRODUCTION

Information delivers a significant business value to organizations in the oil and gas sector (Hawtin & Lecore, 2011). Oil and gas engineering sector covers multiple disciplines and includes both chemical process engineering (designing and applying the equipment for processing the liquids and gasses in the oil fields) and civil engineering (designing and building the infrastructure and the facilities). As a result, there are overlapping and shared challenges between the disciplines, and the development outlined in this paper could be transposed between the disciplines and any other sector with similar business processes and data modeling approaches.

This paper proposes an information integration framework developed as part of a larger industrial research project that aims to improve the information management and delivery across asset lifecycle phases (e.g. design, planning, operations, maintenance and decommissioning). The proposed information integration framework aims to form a single and homogeneous source of accessible and trusted engineering data that can be accessed via the Web from personal computers and mobile devices or integrated with other systems.

Challenges affecting the information management in asset capital projects were identified in the literature and discussed in semi-structured interviews with industry professionals from several large companies, involved in managing oil and gas capital assets. The following sections will present the findings from the literature review, industry interviews and current progress in the development of the proposed information integration framework.

2. LITERATURE REVIEW

Engineering information can be generated in the form of 2D and 3D drawings, process diagrams, technical datasheets, user manuals, etc. by diverse disciplines and applications. As a result data models often suffer from a

Citation: Rasys, E., Hodds, M., Dawood, N. & Kassem, M. (2013). A Web3D enabled information integration framework for facility management. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

lack of a well-structured, standardized information representation (Wiesner, Morbach & Marquardt 2011; Bayer & Marquardt 2004). The ISO15926 standard has been created to address the issues related to different and proprietary import/export schemas (POSC Caesar 2011; Leal 2005). However, due to the complexity and slow acceptance of the ISO15926 standard, software solutions remain fragmented (Smith 2006). An earlier study executed by National Institute of Standards and Technology (NIST) (Gallaher & Chapman 2004) suggested that the capital facilities industry is losing billions of dollars because of the poor software interoperability.

Existing information integration architectures have been described in the literature (Zhang, Li, Zhang, *et al.* 2011; Haas, Miller, Kossmann, *et al.* 2010; Lenzerini, Vassiliou, Vassiliadis, *et al.* 2003):

- Federated architecture uses a mediator engine to present a virtual view of the distributed, heterogeneous data sources as if it was a single dataset. They transform the application queries, retrieve data from connected online services, combine the results in real time and present to the end user or the client application. In such systems the data services have to be available online at the time of query and the speed of the application depends on the complexity of the integration algorithms and the network access.
- Centralized architecture utilizes extract, transform, load (ETL) engines for importing, mapping and cleansing the heterogeneous datasets into a single data storage area. The process can be initiated from the central database (pull action, suitable for online services) or by a client calling a central database service (push action, suitable for loading offline files into the system).

Some sources also mention a third type of architecture – tiered data warehouse (Lenzerini, Vassiliou, Vassiliadis, *et al.* 2003), which aggregates data into a central database, but also stores the copies or summaries of the data at different tiers. There are engines which can combine the federation and centralization approaches and provide both capabilities (Zhang, Li, Zhang, *et al.* 2011; Fagin, Haas & Hern 2009). In such cases the system is populated first, importing the legacy data that still has value, and then additional online data sources are connected into the virtual data views.

Regardless of the approach, fundamental data or schema conflicts can occur when combining data from heterogeneous data sources (Ram & Park 2004). Data conflicts can occur because of the different units of measure, different interpretation of the values or different reliability of the values. Schema conflict encompasses identifier or naming mismatch, different attributes used to define the same data and other structural inconsistencies occurring from the different schema design. In such cases ontologies are used for resolving the schema conflicts and mapping the different project schemas (Wache, Vögele, Visser, *et al.* 2001; Batres, West, Leal, *et al.* 2007).

Besides the general interoperability issue common for all engineering disciplines, oil and gas projects have one specific challenge. Because of the necessity to shorten the project duration a lot of overlapping, concurrent engineering is being done (Wiesner, Morbach & Marquardt 2011). This causes the teams working on detailed design rely on preliminary data, which can substantially change at the beginning of the project causing rework and even project delays. A good change management system is required to control the impact of the changes, also making sure that all required project collaborators are informed when they occur.

Information accessibility and speed is another issue for an information integration framework. It is common for the project contractor in the AEC and Oil & Gas industries to share information and responsibilities with the owner and subcontractors (Schramm, Meißner & Weidinger 2010) while the project collaborators can often be geographically dispersed or located in remote areas (Reece, Hoefner, Seetharam, *et al.* 2008). Engineering web portals provide a single secure access to the project data and provide significant productivity gains due to increased collaboration (Samdani and Till, 2007).

Application speed, reflected by the time spent searching for or retrieving information, impacts the users decisions and productivity (Burda, Crompton, Sardoff, *et al.* 2007), however big enterprises are often reluctant to change the existing systems due to the project requirements (Stonebraker 2010). This is often the case with oil and gas companies, which value reliability and proven track record (Crompton & Gilman 2011). While most sources point to online transaction processing (OLTP) systems requiring the strict SQL (structured query language) data model, the different requirements for data warehouses are often ignored. Studies show that analyzing the requirements and choosing a storage engine optimized for a particular task can increase the performance of an application up to several orders of magnitude compared to a traditional relational database system (RDBMS) (Stonebraker & Çetintemel 2005; Stonebraker, Bear, Çetintemel, *et al.* 2007). There seems to be a mismatch between the increasing need for application speed, accessibility and flexibility, and the commitment to the old technologies, which often limits the performance of the overall solution.

3. INDUSTRY INTERVIEWS

A total of five expert interviews with project consultants and data managers working in large oil and gas projects for BP, ConocoPhillips and Total have been conducted. The interviewees were guided by the main questions; however they were free to elaborate on data management issues present in their projects. The interviews were aimed at confirming and clarifying the information management issues found in the literature. They also served the purpose of defining the guidelines for the required features of the information integration framework. The results from the interviews and expert opinions are summarized below.

The major questions that had been asked aimed to:

- Identify the information types and formats used when exchanging data between project stakeholders;
- Clarify the current issues present in information management processes;
- Define the industry expectations from a new generation of information management systems;
- Explain the use cases and the need for integrated 3D model functionality.

The results confirmed that issues regarding the poor interoperability of information management systems are still present in current oil and gas capital asset projects. There is no industry standard information exchange format – data is being transferred via various text based files also including Excel files, Access databases and project design documents. Very rarely applications are able to exchange information automatically, often email systems are used to drive the business workflows and exchange the information between the project collaborators.

With up to 500 companies and 1500 people collaborating on a single project, web portals can be an invaluable information resource providing each of the stakeholders with an access to the same data interfaces. Accessibility can often become an issue for mobile staff, such as engineers who operate far from their offices – from hotels or on site. Current remote access methods such as VPN connection are subject to strict security measures and depend on very good network access. Thus a lightweight web application could often result in higher productivity in remote areas.

Well defined workflows efficiently drive the processes in software systems. The interaction between people, processes and software is a complex relationship. The resistance to change could be exacerbated by poor software interfaces – "if the application feels sluggish, people start to lose interest", noted one information manager from BP. There are also different cultures and different customer practices around generating engineering data, which make their integration a human issue as much as it is a technical issue. If people feel constrained by poor workflows or slow software, they tend to create their own data stores (e.g. spread sheets) because they are faster or more convenient to work with. In such cases people communicate the changes through emails, but managing the changes is very difficult in such a decentralized system. Once the original email have been forwarded, it becomes nearly impossible to check who has seen what information, and until the document has been submitted to the management system it is impossible for other collaborators to know of any changes that are occurring. Managing the changes in a timely manner is crucial. If missing or incorrect information is detected later in the project, it might be very costly and time consuming to replace that information as the engineers responsible may have already left the project.

The requirements for the 3D model integration are still maturing as not all companies have the 3D model representation as a requirement in the early project stages. It is expected however that the 3D model of the facility would be used in (remote) operations, maintenance planning and safety training, especially if the facility has not been yet completed or is difficult to access. It is worth noting that due to the file sizes, broadband limits and the different needs of various people working on the 3D model, there is a requirement to have two 3D model representations: a review link for a quick review of the model, and a download link, where engineers can access and download the actual model when there is a need for corrections.

It is clear from the above that a wide range of aspects relating to business processes, communication between people and software interoperability needs to be considered and they cannot all be addressed in this paper. In this paper, we focus on the integration and delivery of information and 3D content over the Web by proposing a framework and developing a proof-of-concept tool. The proposed framework and obtained results can be utilised by field researchers to advance the research and development in this key area and by industry developers to improve their systems.

4. INFORMATION INTEGRATION FRAMEWORK

4.1 Architecture overview

In order to achieve the aim of a single homogeneous data source and considering the results of the literature review and the interviews, objectives for the information integration framework have been defined. The integration system needs:

- To be web based and provide web service and client interfaces;
- Utilize an efficient storage layer for storing and retrieving different types of engineering data;
- To be driven by an ontology, which is called Class Library in the field of oil and gas projects;
- Has audit and change management capabilities;
- Integrates a current Web3D technology to deliver the 3D content to the client browser.

The framework proposed in this paper adopts a centralized data storage approach for the heterogeneous engineering information (Figure 1). The object data model in oil & gas sector has its own distinguishing requirements. Each object (called a *tagged item*) has a unique identifier within a facility, a name or description, type of the object (class), a set of possible attributes and associations. Handle identifiers (CNRI 2013) are used to make the objects globally identifiable and resolvable. While part of the data schema is fairly static, the number and values of the attributes can vary greatly, as well as the possible associations to the other tagged items or documents.

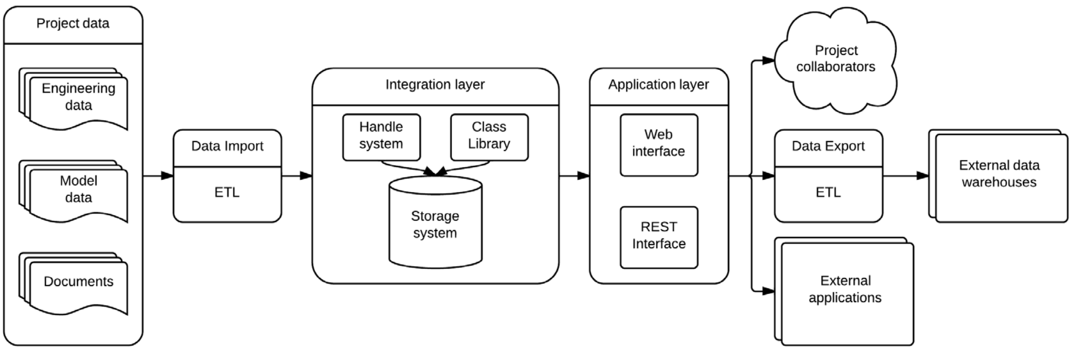


Fig. 1: Integration framework diagram

Data requirements are defined in the ontology called Class library. The role of the Class Library is to define the attribute data that is expected for a given object. Classification of the objects can be carried out by the Class Library through the use of class name mappings (to interpret given object classification into known classes in the Class Library), or through the use of an Engineering Numbering Specification (ENS), which interprets object classification based on the identifier codes. Class Library also provides validation rules for attribute values, such as accepted lookup values (typically for attributes with plain text values), or accepted units of measure for attribute values (typically for attributes with numeric values).

ETL processes use the predefined data requirements and mappings and import data from various data sources into the central data store. The web interface can then be used to search and browse the information. A representational state transfer (REST) based interface makes data available to applications able to consume this type of service. Such framework requires an efficient data model and data storage system and a semi-structured data model has been chosen for this task.

4.2 Semi-structured data storage

Document or semi-structured data models are used to describe data, which does not have a strict schema or it evolves over time (Papakonstantinou, Garcia-Molina & Widom 1995). Current popular formats for the semi-structured data are JavaScript Object Notation (JSON) and Extensible Markup Language (XML). Both of these formats are self-describing, but JSON is more compact and querying JSON objects does not need a separate language to access the attributes.

JSON has been chosen to store the data model in the database as it suits the domain model better than the key-value or relational database systems (Rasys & Dawood 2012). Such storage makes the planning and development of the database schema easier as it closely resembles the human readable representation of the data as shown in Table 1.

Variable number of attributes enables iterative system development, which can be executed using the agile project management (Larman 2004). The system can be started small and provide basic functionality initially; over time additional functions can be added as the database layer can be easily extended without taking the existing application offline.

With client JavaScript code already present in the majority of interactive web applications, usage of client side JavaScript libraries like Knockout.js (Sanderson 2013) simplifies the development of rich client interfaces. Having this format at the storage layer, combined with a JavaScript based application server such as Node.js (Joyent 2013), means that JSON format could be the only form of information needed in the whole path from the database to the client browser. This saves significant development time as data can be extracted from the database, manipulated and passed to the client using the same programming language constructs.

Table 1: Human readable and JSON representation of the data compared.

Human readable data	JavaScript Object Notation (JSON)
Pump (P-101)	{ "ID": " P-101",
Class: Pump	"Name": " Pump P-101",
ID: P-101	"Description": "Cold water pump, floor 2",
Description: Cold water pump, floor 2	"Class": "Pump",
Pressure Max: 80 psi	"Attributes": [
Type: electric	{“Name”: “Pressure Max“, “Value” : 80, “UOM” : “psi"},
Voltage: 380 V	{“Name”: “Type“, “Value” : "electric“},
…	{“Name”: “Voltage“, “Value” : 380, “UOM” : “V"}, …]}

As JSON data format seems suitable for the database layer, several JSON based databases were considered and one called MongoDB (10gen Inc., 2012) was chosen as the storage engine. MongoDB was selected over other JSON databases because it supports multiple indexes and has a query language similar to SQL. It is designed to be scalable and features like GridFS (for storing large files) and geospatial indexing are additional features worth exploring when developing 3D integration. MongoDB is actively maintained and developed, while clients choosing this database engine can get commercial support, which is rarely possible with other free solutions.

Performance benchmarks have been done on Amazon’s AWS cloud infrastructure - EC2 large machine instances, each with 2 cores and 7.5GB of memory. The scripts were run on the Ubuntu 11.10 64bit operating system. The database versions available at the time were 2.0.2 for MongoDB and 5.1.58 for MySQL. Every MongoDB collection and MySQL table had two indexes – one for the primary key and one secondary index.

Test scenarios were created to emulate a large data process job for importing *tagged items* and their *attributes* into the system with a huge number of write and/or read operations taking place sequentially. For these tests it was assumed that each *tagged item* has 100 *attributes*. As it is a prototype data store model test, the performance metrics should not be treated as absolute values, but rather as relative performance indicators.

To benchmark the performance of the database storage layer, write and read operation tests were developed (Rasys & Dawood 2012). For write operations MongoDB is consistently faster than MySQL implementation even as the number of records in the databases increases (Figure 2). Read operation performance (Figure 3) shows a different picture as it only takes one operation for MongoDB to retrieve the *tagged item* along with its *attributes.* MySQL on the other hand needs to join two tables together and this starts to become an issue once the database grows to 10 million *tagged item* records. From that point the performance of MySQL decreased a lot quicker than the MongoDB database, which showed a nearly linear scalability.

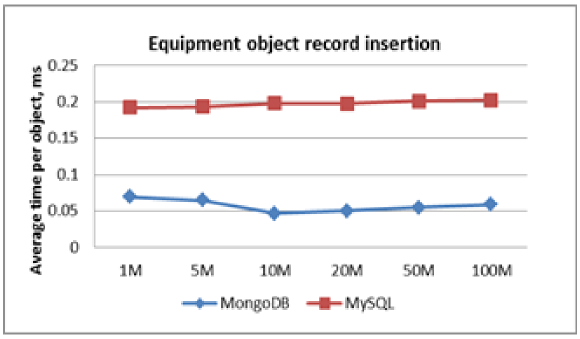


Fig. 2: Write Operations

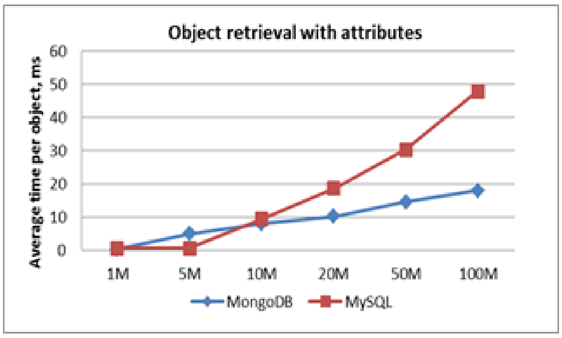


Fig. 3: Read Operations

The performance benchmarks indicate that JSON is a feasible way for storing project data in the database, and that MongoDB is faster than MySQL when the amount of database records is large. Other studies have also shown the superiority of MongoDB in their particular domains (Boicea, Radulescu & Agapin 2012; Jokić, Krčo, Dejanović, *et al.* 2012). As a result, MongoDB has been chosen as the database storage engine for the information integration framework.

4.3 Implementation of the web interfaces

4.3.1 REST interface integration

Some of the issues identified in the interview of industry experts concerned the linking relationships between the equipment items and the design documents. In this paper we demonstrate how a two-way communication between the 3D model components and additional engineering information, received from other stakeholders, can be achieved. Clicking the equipment item in the component list should highlight/display the selected object and vice versa – selecting an item in the 3D model should bring up the data, associated data with that equipment. The usual approach in the design review applications for showing a component of interest is to load up the whole model and then hide the unnecessary elements. For this type of usage, a REST web service and a sample plug-in for NavisWorks Manage has been developed (Figure 4). It allows retrieving associated data via REST interface and displaying it in the application plugin pane or opening the web portal in a separate browser window. The implication of this functionality is that the engineers who are conducting design review are no longer disconnected from the rest of the domain data.

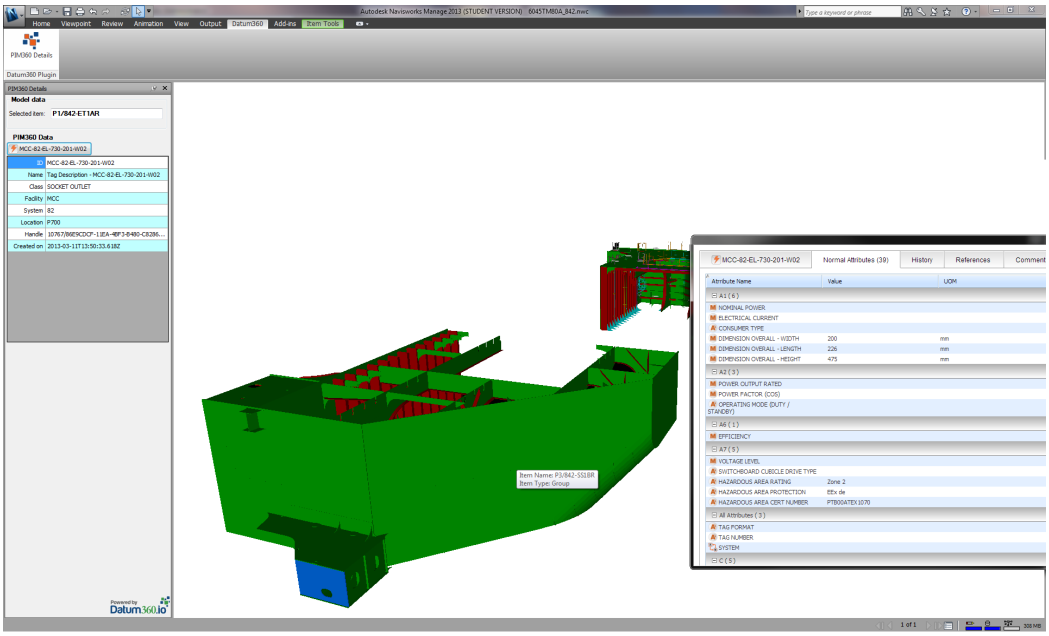


Fig. 4: NavisWorks Manage plug-in links 3D content with the extended engineering information

However, as some of the capital asset models can be very large, loading the full model is not a practical use of processing resources and bandwidth. While a multi-story building model can be sliced by floors, a complex FPSO (Floating Production, Storage and Offloading unit) or sea platform is much more challenging and complex to separate into areas or systems. Also a design review application may not be a viable option for the client operating systems (Linux, Mac OS, tablets). A web-based approach would make the 3D content much more available and accessible. It should also enable a more efficient method of loading only the component(s) of interest for each stakeholder. Such approach would make 3D visualization possible even on portable devices with low power 3D graphics hardware. To implement such a feature the 3D model elements have to be extracted, stored in a predefined structure and mapped to the individual *tagged items* stored in the database. These operations are discussed in the following paragraph.

4.3.2 Proposed Web 3D integration

A lightweight delivery of 3D content over the Web has been identified as one of the key requirements for enhancing the accessibility to engineering information. For a Web3D based model presentation multiple 3D frameworks have been considered. Indeed, there are multiple ways to display 3D content inside web browsers. Many of them are implemented using browser plugins (Behr, Eschler, Jung, *et al.* 2009; Wright & Madey 2008), which create a separate virtual environment within a browser, isolate the Document Object Model (DOM) tree, events and Cascading Style Sheets (CSS) features (Sons, Klein, Rubinstein, *et al.* 2010). WebGL is emerging as one of the most popular base frameworks for the 3D content presentation (Ortiz Jr., 2010), and is supported natively on some browsers (i.e. Chrome) and with certain requirements/exceptions on others (i.e. Firefox, Opera, Safari).

Microsoft Internet Explorer browsers do not support WebGL natively because of the security flaws in the previous WebGL implementations, identified by Context Information security in their report (Forshaw 2011; Microsoft 2011). Such flaws allow malicious code to be run, which either renders the machine unusable or puts “users’ data, privacy and security at risk”. Browser vendors have responded to the report with various means – blacklisting the video cards and drivers with known security issues, restricting the use of the WebGL textures as per cross-domain (CORS) policy (Khronos Group 2011). Such measures and the increasing popularity of WebGL applications forced Microsoft to reconsider their approach and the information on Windows Blue and Internet Explorer 11 indicates that Microsoft intends to add support for WebGL (Thurrott 2013).

WebGL is a low level Application Programming Interface (API), a JavaScript wrapper over OpenGL 2.0 ES functions. Its specification does not define any file formats and therefore it is not designed to natively support any 3D file standards. Web applications utilizing WebGL often define their own data structures and the lack of universal 3D format support makes the data exchange between the design and client applications difficult.

Numerous libraries that use WebGL as their rendering engine have been created. They abstract the low level functions into API calls, which deal with vertices, objects and scene graphs. While some of the libraries try to tie the existing standards, e.g., X3D (Behr, Eschler, Jung, *et al.* 2009), others deviate from that and focus on making the most of the underlying platform and the rendering engine. Several library implementations have data converters, which can convert 3D content from the more popular standards (IFC, FBX) to the internal structures that the libraries use. SceneJS is one of such libraries and it creates a JSON scene graph, which can be easily manipulated by a JavaScript application engine. It employs numerous optimizations to increase the rendering performance (SceneJS group, 2012). An open source BIM Surfer project, which uses SceneJS as the visualization engine, already exists (BIM network, 2011), but there are no known design and CAD applications that would produce SceneJS JSON file as the export format. However, an open source BIMserver project (BIM network, 2012) can be used as a transformation step. This allows taking a model from a design application (i.e. REVIT), exporting it to IFC format, importing it into BIM server and exporting it as the SceneJS JSON format, which can be used by an application using the SceneJS library.

Three.js is another high level JavaScript library. It is fast, object oriented, supports math operations and has an extensive support for the file formats in addition to its own JSON and binary formats (three.js 2013; Parisi 2012). Choosing between the libraries is not an easy task as they evolve very quickly. Initially SceneJS was chosen as the library for the framework, but it has been observed that some of the model data is being lost during the transformation trough the BIM Server. While BIM Server is an open source project, it does not seem to have a large community and the support for the additional file formats seems difficult to implement. SceneJS project itself seems to have stalled as the latest available version is more than a year old. After considering these issues, three.js has been selected as the intermediate 3D framework.

Three.js has a native JSON file format support and content can be imported from engineering design review applications (e.g. NavisWorks) via FBX file converter. Since the output native JSON file is just a plain text file, it is trivial to write an extraction/mapping routine, associating the 3D coordinates, material, lighting, rotation of a component with the *tagged item* stored in the database. As the same *tagged item* can be present in multiple models, the following mapping schema has been proposed to link the 3D data with the *tagged item* identifiers:

```
"hdl" : "10797/a9a30061-76b0-4c15-8f2a-6efa74371612"
"src" : "FPSO 1"
"id" : "FLANGE 1 of BRANCH /J70-PIPE-TEST/B1"
"geometry" : {},
"material" : "",
"position" : [ 0, 0, 0 ],
"rotation" : [ 0, -0, 0 ],
"scale"     : [ 1, 1, 1 ],
"visible"   : true
```

The first property (hdl), which denotes the unique object identifier (handle), identifies the object within the integration database. The next two properties (src, id) represent the drawing or model and the identifier within that model. The geometry property needs to have the 3D data in accordance with the three.js data specification. The combination of these properties allows linking geometric shapes from different drawings or models to a single set of engineering tagged items. Such linking enables the delivery of the tagged item information alongside its context specific 3D representation to a web browser (Figure 5):

Possible usage scenarios include getting the data in a single discipline for a particular subsystem in a particular area. Querying can also be done on the attributes so it becomes possible to obtain the equipment from a particular

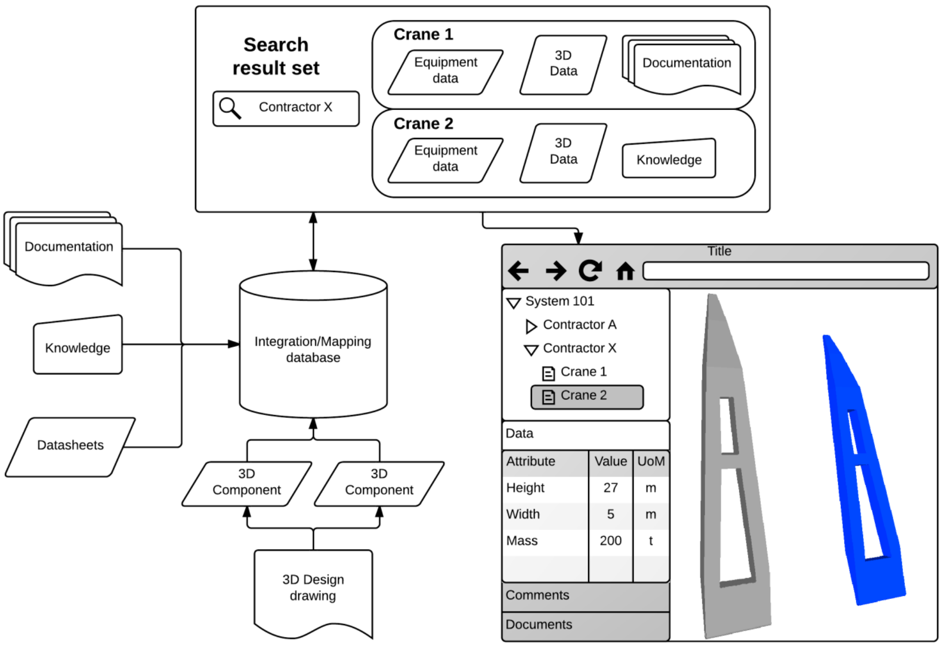


Fig. 5: Dynamic assembling of the scene, based on a query

supplier or the equipment for certain flow rates and display that information together in a web browser window. This proposed solution, while still under development, is promising in terms of its ability to present the slices of information relevant to each particular user.

5. CONCLUSIONS AND FUTURE WORK

This research identified the issues and challenges affecting the management of engineering information in the oil and gas engineering field using semi-structured interviews with industry experts from large oil and gas companies. To address some of those challenges, in particular those related to the heterogeneity of information and the speed and access to information, an information integration framework was proposed. The framework was prototyped in a proof-of-concept tool that proved to be capable of delivering integrated engineering information to client machines from web services and therefore providing a remote access to this engineering information. By employing a semi-structured storage engine, the framework also guaranteed the query speed and scalability to accommodate large data sets of capital asset projects. Furthermore, this research presented the concept and discussed the feasibility of the web interface that can make engineering information available for both external applications and project collaborators directly via their web browsers. The proposed features of the concept enable the selective displaying of 3D model elements along with the corresponding data from other applications. As a result, this proposed framework can be considered as one step closer to a single trusted and 3D Web accessible source of project facility data.

The additional engineering data and the visualization of 3D model views, whether using a REST data interface or a full web portal, is expected to have a positive impact on the client productivity given the business value of managing information and data identified in both literature and expert interviews. The proposed framework is particularly beneficial for organizations involved in the oil and gas sector, dealing with large quantities of information that is spread over multiple systems. Future work will involve developing additional features to enhance the business workflows and user experience. Examples of such features are: the subscription to changes to better coordinate the collaboration between engineers; the enhanced audit and management of change capabilities, and the augmentation of visualization with heat maps or color coding to identify 3D components that have missing or inconsistent information.

6. REFERENCES

10gen Inc. (2012) *MongoDB*. [Online]. 2012. Available at: http://www.mongodb.org/ (Accessed: 15 July 2012).

Batres, R., West, M., Leal, D. and Price, D. (2007) *An Upper Ontology based on ISO 15926*. 31519–534.

Bayer, B. and Marquardt, W. (2004) Towards integrated information models for data and documents. *Computers & Chemical Engineering*, Vol. 28, No. 8, 1249–1266.

Behr, J., Eschler, P., Jung, Y. and Zollner, M. (2009) X3DOM - A DOM-based HTML5/ X3D integration model. In: *Proceedings of Web3D 2009 The 14th International Conference on Web3D Technology*. 2009 Association for Computing Machinery, 127–135.

BIM network (2011) *BIM Surfer*. [Online]. 2011. Available at: http://bimsurfer.org/ (Accessed: 15 July 2012).

BIM network (2012) *BIMserver*. [Online]. 2012. Available at: http://bimserver.org/ (Accessed: 15 July 2012).

Boicea, A., Radulescu, F. and Agapin, L.I. (2012) MongoDB vs Oracle -- Database Comparison. *2012 Third International Conference on Emerging Intelligent Data and Web Technologies*, 330–335.

Burda, B., Crompton, J., Sardoff, H., Falconer, J., *et al.* (2007) *Information Architecture Strategy for the Digital Oil Field*.

Corporation for National Research Initiatives (CNRI) (2013) *Handle System*. [Online]. 2013. Available at: http://handle.net/ (Accessed: 18 May 2013).

Crompton, J. and Gilman, H. (2011) The Future of Integrated Operations. *SPE Economics & Management*, Vol. 3, No. 1, 45–51.

Fagin, R., Haas, L.M. and Hern, M. (2009) *Clio : Schema Mapping Creation and Data Exchange*, 198–236.

Forshaw, J. (2011) *WebGL - A New Dimension for Browser Exploitation*. [Online]. 2011. Available at: http://www.contextis.co.uk/research/blog/webgl-new-dimension-browser-exploitation/ (Accessed: 19 May 2013).

Gallaher, M.P. and Chapman, R.E. (2004) *Cost analysis of inadequate interoperability in the US capital facilities industry*. US Department of Commerce, Technology Administration, National Institute of Standards and Technology.

Haas, L.M., Miller, R.J., Kossmann, D. and Hentschel, M. (2010) A first step towards integration independence. *2010 IEEE 26th International Conference on Data Engineering Workshops (ICDEW 2010)*, 147–150.

Hawtin, S. and Lecore, D. (2011). The business value case for data management - a study. [Online]. Available at: http://www.oilandgasuk.co.uk/cmsfiles/modules/publications/pdfs/OP055.pdf (Accessed: 15 July 2013).

Jokić, S., Krčo, S., Dejanović, I., Vučković, J., *et al.* (2012) Evaluation of a Document Oriented Resource Directory Performance. *Telfor Journal*, Vol. 4, No. 2.

Joyent (2013) *node.js*. [Online]. 2013. Available at: http://nodejs.org/ (Accessed: 18 May 2013).

Khronos Group (2011) *WebGL Security*. [Online]. 2011. Available at: http://www.khronos.org/webgl/security/ (Accessed: 19 May 2013).

Larman, C. (2004) *Agile and iterative development: a manager's guide*. Addison-Wesley Professional.

Leal, D. (2005) ISO 15926 "Life Cycle Data for Process Plant": An Overview. *Oil & Gas Science and Technology - Rev IFP*, Vol. 60, No. 4, 629–637.

Lenzerini, M., Vassiliou, Y., Vassiliadis, P. and Jarke, M. (2003) *Fundamentals of data warehouses*. Springer.

Microsoft (2011) *WebGL Considered Harmful - Security Research & Defense - Site Home - TechNet Blogs*. [Online]. 2011. Available at: http://blogs.technet.com/b/srd/archive/2011/06/16/webgl-considered-harmful.aspx (Accessed: 19 May 2013).

Ortiz Jr., S. (2010) Is 3D Finally Ready for the Web? *Computer*, Vol. 43, No. 1, 14–16.

Papakonstantinou, Y., Garcia-Molina, H. and Widom, J. (1995) Object exchange across heterogeneous information sources Philip S Yu and Arbee L P Chen (eds.). *Proceedings of the Eleventh International Conference on Data Engineering*, Vol. 67, No. 5, 251–260.

Parisi, T. (2012) *WebGL: Up and Running*. O'Reilly Media, Incorporated.

POSC Caesar (2011) *ISO15926 Primer*. [Online]. 2011. Available at: https://www.posccaesar.org/wiki/ISO15926Primer_Parts (Accessed: 11 May 2013).

Ram, S. and Park, J. (2004) Semantic Conflict Resolution Ontology (SCROL): An ontology for detecting and resolving data and schema-level semantic conflicts. *Knowledge and Data Engineering, IEEE Transactions on*, Vol. 16, No. 2, 189–202.

Rasys, E. and Dawood, N.N. (2012) Semi-Structured Data Modelling for a Web-Enabled Engineering Application. In: *Computing in Civil Engineering (2012)*. June 2012 American Society of Civil Engineers, 41–48.

Reece, C.A., Hoefner, M.L., Seetharam, R. V and Killian, K.E. (2008) *Business Subsurface*.

Samdani, K. and Till, A. (2007) Engineering portals add significant value to E&P project delivery capabilities. *World Oil*, Vol. 228, No. 11, 91-95.

Sanderson, S. (2013) *Knockout : Home*. [Online]. 2013. Available at: http://knockoutjs.com/ (Accessed: 18 May 2013).

SceneJS group (2012) *3D Scene Graph Engine for WebGL*. [Online]. 2012. Available at: http://scenejs.org/ (Accessed: 15 July 2012).

Schramm, C., Meißner, A. and Weidinger, G. (2010) Contracting strategies in the oil and gas industry. *3R International*, Vol. 1, 33–36.

Smith, B. (2006) *Against Idiosyncrasy in Ontology Development*.

Sons, K., Klein, F., Rubinstein, D., Byelozyorov, S., *et al.* (2010) XML3D: interactive 3D graphics for the web. In: Philipp Slusallek, Byounghyun Yoo, and Nicholas Polys (eds.). *Web3D 10 Proceedings of the 15th International Conference on Web 3D Technology*, 175–184. 2010 ACM.

Stonebraker, M. (2010) *Why Enterprises Are Uninterested in NoSQL*. [Online]. 2010. Available at: http://cacm.acm.org/blogs/blog-cacm/99512-why-enterprises-are-uninterested-in-nosql/fulltext (Accessed: 21 July 2013).

Stonebraker, M., Bear, C., Çetintemel, U., Cherniack, M., *et al.* (2007) *One Size Fits All ? – Part 2 : Benchmarking Results*.

Stonebraker, M. and Çetintemel, U. (2005) "One Size Fits All": An Idea Whose Time Has Come and Gone. In: *Proceedings of the 21st International Conference on Data Engineering (ICDE 2005)*. 2005 IEEE Computer Society, 2–11.

three.js (2013) *three.js - JavaScript 3D library*. [Online]. 2013. Available at: http://threejs.org/ (Accessed: 19 May 2013).

Thurrott, P. (2013) *Blue's Clues: WebGL Support in IE 11*. [Online]. 2013. Available at: http://winsupersite.com/windows-8/blue-s-clues-webgl-support-ie-11 (Accessed: 19 May 2013).

Wache, H., Vögele, T., Visser, U., Stuckenschmidt, H., *et al.* (2001) Ontology-Based Integration of Information — A Survey of Existing Approaches. In: *Proceedings of IJCAI-01 Workshop: Ontologies and Information Sharing*. 2001 Seattle, 108–117.

Wiesner, A., Morbach, J. and Marquardt, W. (2011) Information integration in chemical process engineering based on semantic technologies. *Computers & Chemical Engineering*, Vol. 35, No. 4, 692–708.

Wright, T.E. and Madey, G. (2008) A Survey of Collaborative Virtual Environment Technologies. *University of Notre Dame-USA, Tech. Rep*.

Zhang, S., Li, J., Zhang, F. and Li, X. (2011) Design of Data Center and Implementation of Data Integration Based on SOA Framework, 267–271.

EXPERIMENTAL INVESTIGATION OF USING RFID INTEGRATED BIM MODEL FOR SAFETY AND FACILITY MANAGEMENT

Cheng Zhang, Jia Chen and Yifan Yang
Xi'an Jiaotong-Liverpool University, China

Amin Hammad
Concordia University, Canada

ABSTRACT: *This paper proposes a new system integrating radio frequency identification (RFID) and building information modeling (BIM), which can be used for the lifecycle management for buildings. During the structural and MEP design stage, the locations of permanent tags are designed for facility management purpose. Tags can be designed to be attached to concrete structures, steel structures, ventilation pipes, sewerage pipes. Location information and other information can be written in and retrieved from the tags. During the construction stage, the locations of temporary tags are planned for safety management purpose. Tags can be attached to doors, windows, protection fences, and other temporary safety measures during construction. Space in the BIM is classified into workspaces with different risk levels according to work breakdown structure (WBS) and schedules. Algorithms are proposed for automatic risk analysis using the BIM, which is updated to reflect the real situation on site, resulting in risk-ranged workspaces. RFID receivers are installed on the critical locations on site. Once a tag is detected for specific safety measures, the risk of that workspace will be reduced. Workers also carry tags and their locations can be monitored. Once a worker enters a workspace with high risk, signals can be sent to the worker to remind him/her about the situation. In extreme cases, an alarm is triggered to ask the worker to leave the dangerous workspace. A case study is undergoing to apply the proposed approach on a construction site in Suzhou, China.*

KEYWORDS: *Safety, RFID, BIM, Workspace, Lifecycle, Facility management.*

1. INTRODUCTION

Construction sites are dynamic and on-site situations are changing in terms of permanent and temporary structures and facilities; therefore, information of the construction site should be updated based on the project progress monitoring. Radio Frequency Identification (RFID) is an affordable technology that can be used to collect information for the lifecycle management of a building. Starting with the transportation of construction material, RFID is widely used for tracking the raw materials, precast structural components, and other building facilities (Furlani and Pfeffer, 2000; Song et al., 2005; Song et al., 2006; Torrent and Caldas, 2009). The purpose is to enable lean construction and to reduce storage and labor costs, etc. Location data collected from RFID tags can be used to update construction processes in real-time (Ghanem and AbdelRazig, 2006). Small tools and other objects on site can be tracked to facilitate an efficient construction management (Goodrum et al., 2006). In addition, applicability of RFID technology in construction has been investigated in terms of feasibility, accuracy and reliability, such as Pradhan et al. (2009); Lee et al. (2012); Taneja et al., (2012);

Usually, information saved in those RFID tags attached to components includes the material/component name, type, date of manufacture, transportation, and installation, etc. depends on the characteristics of the material/components. That information can be collected and integrated into a digital model of the structure and analysis can be applied for all kinds of management purposes. For example, Building Information Modeling (BIM) is such a model with the capability in integrating information from different sources. BIM is a new approach to design, construction, and facilities management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format (Eastman and Eastman, 2008). Therefore, it is natural to integrate RFID and BIM technology to build the linkage between physical tags attached to building components and the virtual digital model. As indicated by Motamedi and Hammad (2009), a more efficient facilities management system can be built by sharing and exchanging distributed data resulted from the integration of RFID and BIM.

Citation: Zhang, C., Chen, J., Yang, Y. & Hammad, A. (2013). Experimental investigation of using RFID integrated BIM model for safety and facility management. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

During construction, it is important to identify risks on construction sites so as to eliminate them before accidents occur. Safety measures are mandatory on site to prevent accidents; however, an effective way is missing to check if those measures are taken properly on construction site, and workers on site are not given enough awareness about where are those dangerous areas. For example, although regulations are defined to use guardrails, safety nets, harnesses, etc., to prevent falling, out of the construction workers that suffer fatal injuries, more are involved in falls than any other single cause (Huang and Hinze 2003). Therefore, tracking or monitoring safety measures (e.g., guard rails) on site should be applied for an effective safety management. This information can also be reflected and integrated by using the BIM. Kiviniemi et al. (2011) have used BIM as a 4D safety planning tool, in which the researchers have indicated that BIM technology can present a new way to solve site safety problems. However, the virtual barriers generated in their project are static and for visualization purpose only, and there is no real-time safety management using those virtual barriers.

The authors of this paper have investigated the feasibility of accurately locating dynamic virtual fences (DVFs), which are generated along hazard zones to prevent workers from falling or other hazardous (Zhang et al., 2012). The heights of the DVFs are determined by the height required for the guardrails, which should be at least 1.2 m above the surface on which the worker is working according to the safety code. However, real-time warning is an issue that needs to be investigated more to provide reliable protection. Ultra Wideband (UWB) devices have been investigated to be applied on construction site for monitoring moving objects on site and checking the presence of safety measures. Although the accuracy claimed from UWB devices is up to 15 cm in an ideal condition, the cost of the UWB system and disturbing to the construction site need to be investigated more. Compared with a high accurate UWB system with high cost, RFID can provide approximate location information with a considerable lower cost. In addition, data can be written into the memory of the RFID tags to store information regarding the properties of the object, which is not applicable for UWB tags. However, delicate design is needed to maximize the advantages of this affordable technology as much as possible.

Based on the experience of the authors in applying radio frequency technology and BIM modeling, the present paper proposes an approach of building a spatial network in the BIM model by registering permanent and temporary RFID tags in the building model, which will be used as a base system for various management that are related to spatial problems. During the current research stage, focus has been put on safety management and facility management during the lifecycle.

2. OBJECTIVES

The proposed research aims to investigate the effectiveness of integrating RFID with BIM for safety and facilities management based on a spatial network. The objectives of the present paper are: (1) to investigate the topology of tag network based on the requirements from safety and facility management; (2) to propose an algorithm for defining workspaces based on schedule and reference objects; (3) to propose an approach for automatic risk assessment during construction process; and (4) to automatically check whether the physical barriers/barricades are installed in the proper locations with proper dimensions.

This proposed method is part of a big vision, which integrates BIM-based safety prevention system with RTLS environmental perception system. The ultimate goal of this research is towards a Smart Construction Site (Zhang et al., 2009) and eventually a smart building can be established by utilizing data collection through sensors embedded in the structures. Furthermore, with all kinds of sensors embedded, data of the operation situation of the building can be collected automatically and transferred wirelessly to facilitate an effective facilities management system.

3. METHODOLOGY

Figure 1 shows the main concept of the methodology, which indicates the integration of RFID and BIM. RFID tags are attached to building components, safety measures, facilities, and other objects that need to be tracked. During construction, data of RFID tags are collected using handheld/fixed receivers and then transferred wirelessly to the office without interrupting the construction activities. The dashed lines in the figure indicate the wireless data transferring. Data collected from the RFID readers are transferred wirelessly through GPRS the server in the office, considering the availability of other techniques, e.g., Wi-Fi may not be available on a construction site. Location of the RFID tags are calculated based on the RSSI value collected from the reader. Then, RFID tags are registered/represented in the BIM as temporary or permanent objects depending on the requirements of safety management system (SMS) and facilities management system (FMS). Location information together with other data stored in the tags are read and saved in the BIM database. By regularly updating the BIM model, other management systems can be developed, for example, construction management system (CMS) can use the information to monitor the progress of the construction; As indicated previously, this paper is trying to investigate the spatial issues while linking RFID and BIM; therefore, building a network of tags in 3D space in the physical building under construction and reflecting the network in BIM is the main topic that is investigated in the present paper.

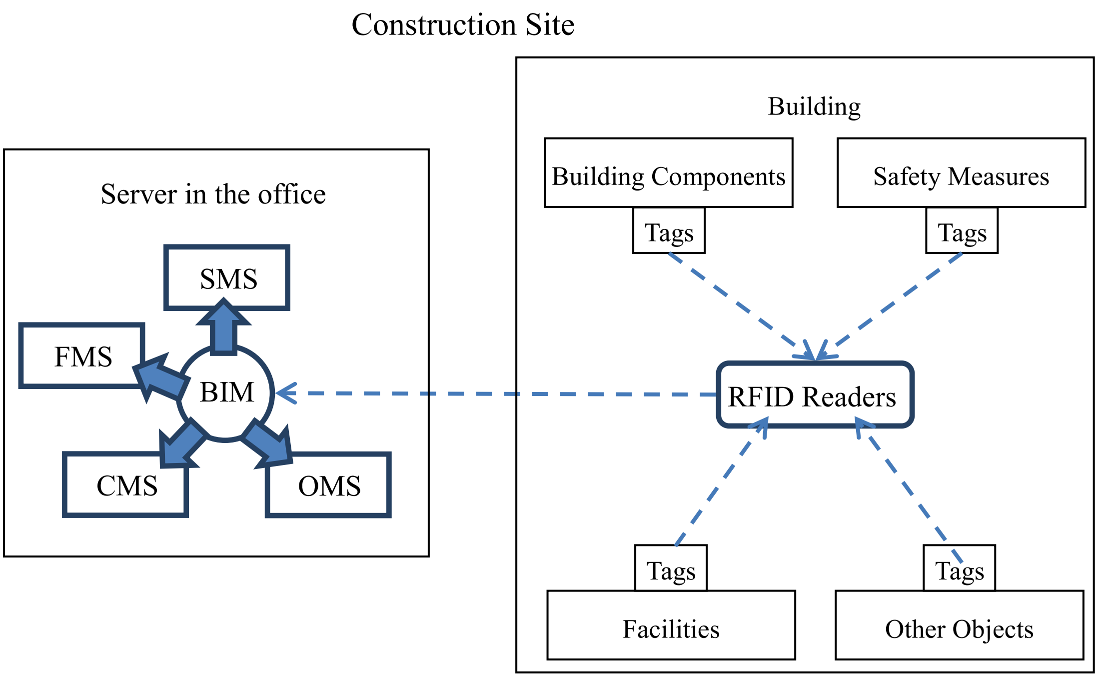


Fig. 1: Conceptual design of integration of RFID and BIM

3.1 Define space-related requirements for safety and facilities management

First of all, the requirements from safety and facilities management should be investigated. For facilities management, tags may be available before transported to construction site. For those tags, information should be collected and tags should be registered in the BIM immediately after the installation. After that, an updating of the tag network should be applied to reflect the changes. Other than those existing tags, careful design should be applied to build a network to facilitate localization. It is ideal to tag all the components to build a complete database; however, this will result in a huge number of tags in the building, and may increase the difficulty in managing scattered data in a centralized database. In order to have a cost-effective system, tags will be attached to components that have distinguished spatial characteristics and cost-effectiveness should be taken into consideration. For example, the scale of the project, types and values of the components will be considered (Motamedi and Hammad, 2009). Therefore, hierarchy is defined to build an effective network according to level of details required. A primary network is built with tags with known locations accurately. Coordinates of those tags are designed for major building structures, for example, major columns. A secondary network is built to indicate the space divisions once the building is under operation, for example, doors and windows. A third level network is built to indicate the facilities in the building, for example, fire extinguishers, and other fixed assets. Information written in those tags should include tag ID, name of objects attached, location, which is different based on different levels, etc. For a primary network, coordinates should be provided; for a secondary network, room number is enough to identify the location of the tag; other descriptions, such as ‘near room X’, can be used to define the location of tags in the third level network.

For safety management, construction safety code should be reviewed and risks with spatial aspects will be extracted and to be represented in BIM. The main category includes protection against falling, scaffolding, confined spaces, electricity safety work zones, and heavy machinery safety work zones (Hammad et al., 2012).

Tags are attached in a way that the height, length or/and width of those safety measures can be calculated based on the number of tags and the data stored in the tags. For example, fixed interval is predefined as 5 m for tags attached to guard rails, and the height of the guardrail is saved in the tag's memory.

3.2 Location design of permanent and temporary tags

Visibility and effectiveness should be considered when deciding the location of tags. Permanent tags are designed in a way to facilitate a long-term data collection purpose for facility management. As described in the previous subsection, three levels of networks will be built to tag different objects. The whole network is built following the progress of the building, which means the network will be partially built during the construction and updating is needed to reflect the real situation on site. Therefore, it is important to ensure there are enough tagged objects to make the network function properly. The simplest way is always have at least four primary tags in the partial network; thus, the approximate location of other tags can be estimated by using trilateration.

In addition, tags should be visible to the reader/receiver in the case of fixed readers/receivers are used. Tests should be applied to the RFID system that is selected for the construction project to investigate the range of the reader/receiver and the visibility of tags. A range test is discussed in Subsection 5.1. A tag's location can be decided using trilateration based on four tags with known location. However, due to the approximate location that RFID system can provide, accurate localization is not feasible. Therefore, buffers will be used to identify the locations of tags according to the properties of the RFID system used in the construction site.

3.3 Define and identify space in BIM model

Space identification is important for safety and facilities management. In a BIM model, space will be classified into two major groups; one is workspaces during construction, while the other is based on the functioning areas of the building. Those two spaces are interrelated but will be defined in a different way. During design stage, space in a BIM model can be created in different ways depending either on the functions available in software tools or designers' habit. Zones, rooms, spaces, are defined differently with various tools or convention. The essential is that the designer should bear in mind the rules for creating spaces that can facilitate the data retrieving from a designed model. Other than the functioning areas, space during construction is also important for safety management. The most vital risk on construction site is falling (Huang and Hinze, 2003). Therefore, openings on the slab, the walls, and the roof are drawing the attention of the authors of this paper. To automatically identify risks related to falling, how to extract the location information of the openings created in the BIM model should be investigated. For example, the coordinates of the bottom left and the upper right corners should be identified automatically.

During construction, workspace identification is applied for each construction task. Work breakdown structure (WBS) is used to create the hierarchy of the tasks and subtasks of the construction project. Each WBS deliverable is associated with a reference object, which can be building components including Mechanical, Electrical and Plumbing (MEP) components, and temporary structures. For example, for installing HVAC ducts in a room, the sections of ducts are identified as reference objects, which will be tagged ideally. The length, height from the floor, and the location of a section is retrieved from the BIM model. The installation task is further divided into subtasks, such as fixing the studs to the ceiling for hanging the ducts. In this case, a scissor lift may be used to help the worker reach the ceiling. Thus, the workspace of the ducts installation task is defined based on the reference object (section of ducts), and dimension of the scissor lift, for that specific task duration. The height of the workspace is equal to the maximum reaching height of the worker, which is the height of the room. A buffer is added around these dimensions to create a box-shaped workspace for the subtask. After the workspace is identified, automatically risk assessment can be applied.

3.4 Automatic risk assessment of space

Schedule will be linked with each construction task. Time intervals will be decided to generate workspaces and risk assessment will be applied to those workspaces. The assessment will be done for the whole building in a backward direction opposing to the building procedure. A basic assumption can be made is that once the building is built and ready for operation, risks will be reduced to 0. At the beginning of the stage, which means a completed building, an initial risk level 0 will be assigned to each workspace, either can be a room, a zone, or the workspace based on WBS. Rules are developed to evaluate the risk of each workspace. If the walls of a room are partially built at a specific time, risk level will be decided based on the ratio of completeness. For example, if an exterior wall exists in the area and only 20% is built, which results in a wall with a height of 60 cm. By comparing this value with the safety code, a physical fence should be installed to prevent falling risks. Therefore, the risk level of that workspace will be increased to 10. Similar rules can be developed to evaluate the risk level of associated spaces with openings that falling may happen. For example, the lower left and the upper right coordinates of an opening can be found and will be used for defining a buffer for detecting safety measures. Based on a predefined time interval, risk level of each workspace can be evaluated based on information extracted from the safety code (Hammad et al., 2012). This assessment result is acted as an input during construction stage. Location information of tags are collected and used for updating the BIM model. If tags are detected in a workspace indicating that a guardrail is installed around that area, the risk-level of that space will be reduced to 5. Otherwise, a warning will be sent to remind installing safety measures. A flow chart is shown in Fig. 2.

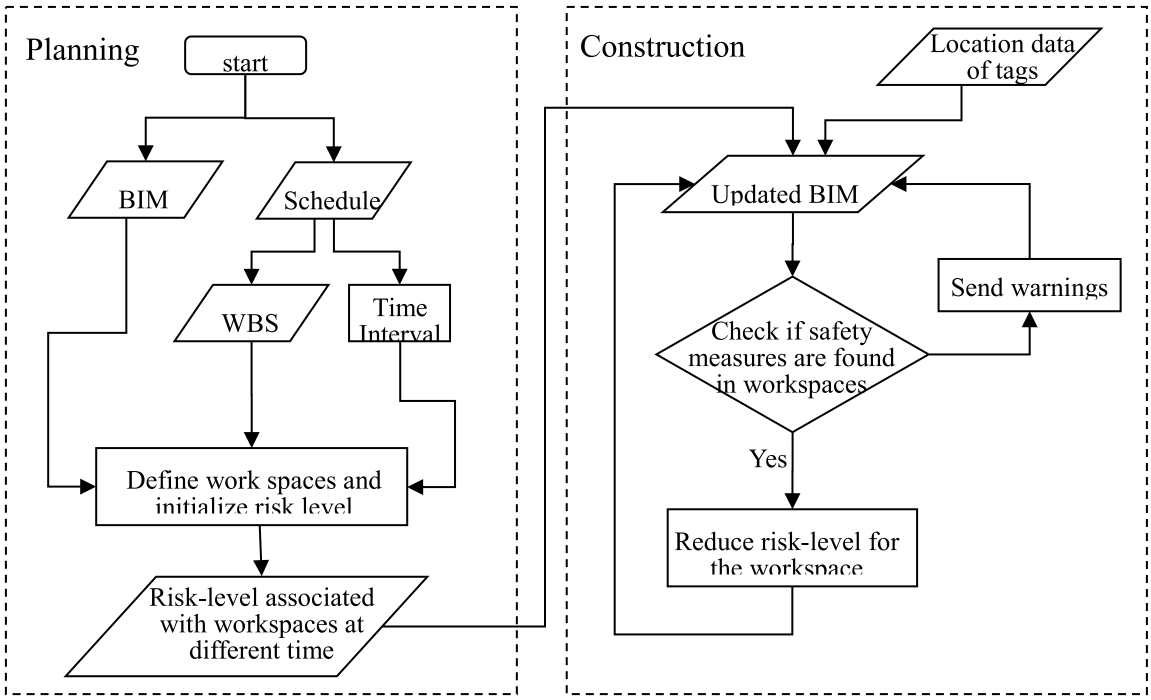
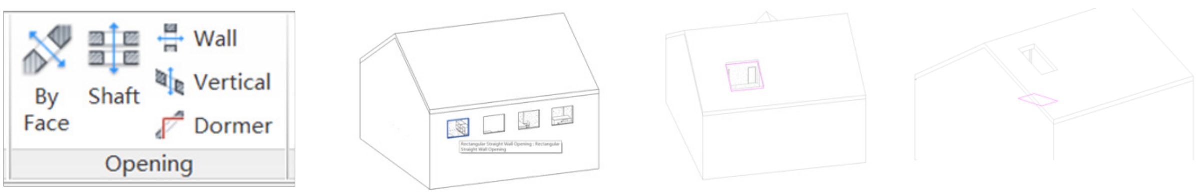


Fig. 2: Flow chart of automatic risk-assessment

4. IMPLEMENTATION

Revit from Autodesk is specially developed for building information modeling, as a BIM authoring 3D design tool. To be more productive, it is preferable to start the Revit model based on a 2D drawing. Revit provides importing CAD or linking CAD option to relate CAD and the difference is whether the Revit model will automatically reflect changes to original CAD file. In Revit, any enclosed spaces can be defined as rooms and the most common room boundaries are walls, doors and room separate lines. Each wall added in the model defines a room boundary by default. Room separate lines are imaginary lines but visible in view to add and adjust room boundaries. In addition, rooms are phase-specific, which means the function of space varies with reference to phases.



(a) (b) (c) (d)

Fig. 3: Creating openings using functions available in Revit

There are several functions available in Revit to create openings vertically or perpendicular to the surface, as shown in Fig. 3(a). 'By Face' means creating an opening perpendicular to the selected face (Fig. 3(c)) while 'Vertical' means creating an opening perpendicular to a level (Fig. 3(d)). 'Wall' is specified to cut a rectangular opening in a straight or curved wall (Fig. 3(b)). If designers want to cut round or other shapes openings in the wall, they need to edit the profile of a wall. 'Dormer' is a combination of vertical and horizontal cuts for dormer openings. In addition, 'Shaft' creates a shaft opening, which is normally more than two floors, by defining a subterranean level and a penthouse level, as shown in Fig. 4. Each opening created by those functions is allocated a unique ID and the location of the opening can be represented by coordinates of lower left point and upper right point assuming the opening is a rectangle parallel to x, and y axis of the coordinate system. If the opening is irregular, it is recommended that placing some small generic models at the critical corner of the space to represent the location. Plug-in is developed to search the openings on the walls, floors, and other structures, and safety measures are generated accordingly. A flowchart is shown in Fig. 5.

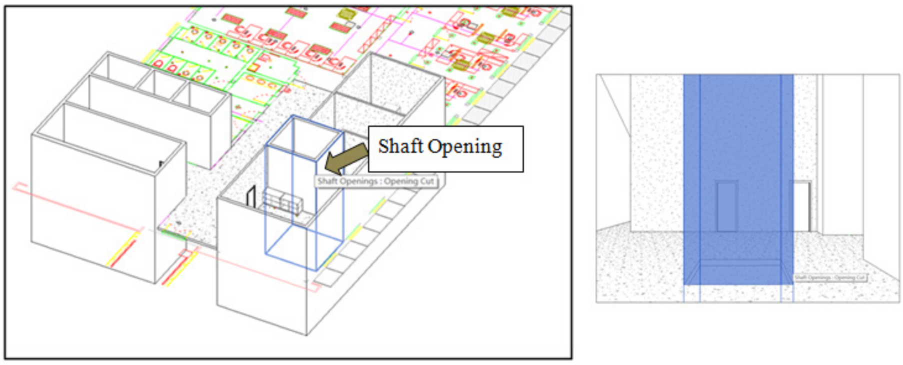


Fig. 4: Creating a shaft opening for elevator space

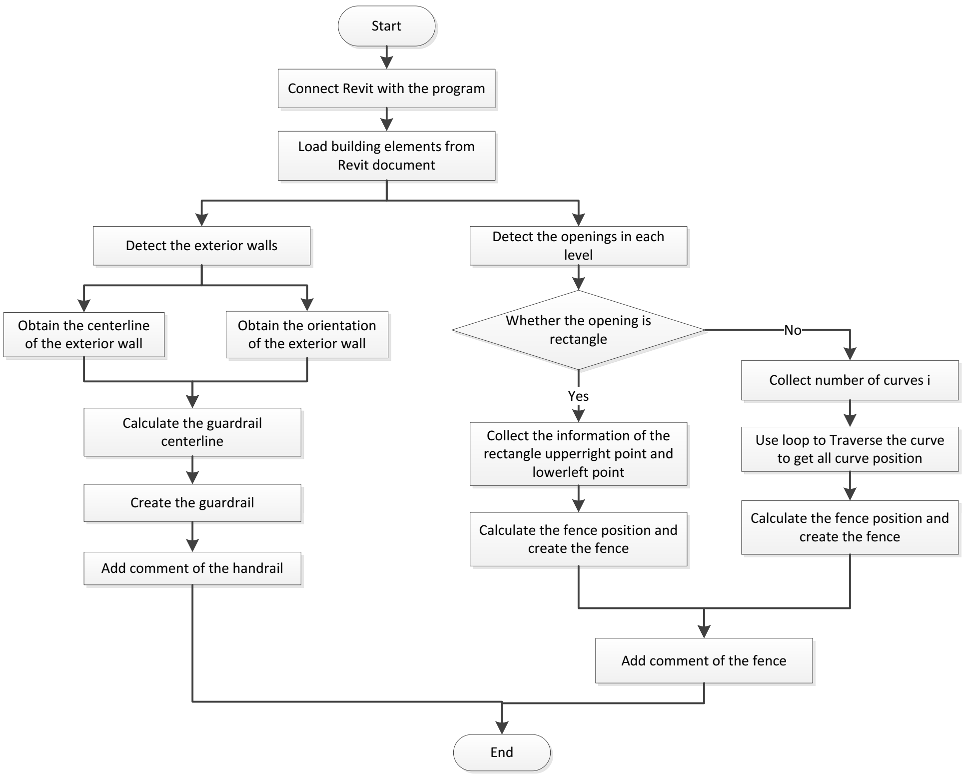


Fig. 5: Flowchart of opening detection

Revit API filter is used to search components, e.g., exterior walls and openings. If an exterior wall is found, the centerline and the orientation of the exterior wall are obtained. Based on that information, guardrail is created accordingly with some offset to the exterior wall (Fig. 6(a)). It should be noted that exterior walls usually extend along several floors; therefore, extra judgment is made to create guardrails on different levels. At the same time, openings are detected on each level, either on the floors or on the exterior walls. If an opening is found, relative information is obtained, such as the lower left and the upper right points, or the curve numbers. Fences are created around the openings (Fig.6 (b) and (c)) based on information obtained from the BIM model. The newly created objects, guardrails and fences, are created as new Family, which can store information in the Property, which includes host of the object, the level, the reference object, etc.

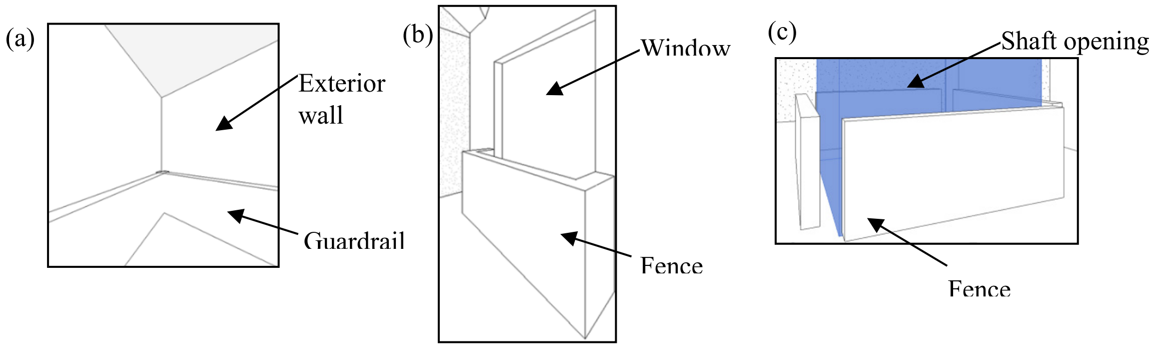


Fig. 6: Guardrails and fences created for exterior walls and openings

A 2.4G Hz RFID system is selected to be tested in this research. Passive and active tags are both used to test the visibility and effectiveness. Locations of tags are calculated by trilateration based on at least four tags with accurate location information. Distances between tags are decided according to the Received Signal Strength Index (RSSI). Due to the limitation of the accuracy that RFID system can provide, approximate location of tag is used to check the completeness of structures and the installation of safety measures. However, information stored in RFID tags can somehow compensate the inaccuracy of locations. By retrieving the name of the object that the tag is attached, for example, guardrails, reliability is increased for risk assessment for the workspaces. Plug-ins are developed to load data collected from the RFID tags into BIM and to create corresponding tags in the model to build the proposed hierarchical network. The major steps are described as follows:

(1) Initialization of the tag network: fixed readers are installed on site, several tags are attached to permanent structure with measured distances, and the locations of those tags are calculated. Tags with known locations are represented in the BIM model; (2) Fixed/handheld readers will continuously collect readings from all RFID tags within the range to obtain the tag ID, RSSI, and the pre-written data, such as the reference object (guardrails, safety net, etc.). Data read are saved in a text file and sent to the server through GPRS; (3) The approximate locations of tags are calculated based on the RSSI values. Other information obtained from the tags is also taken into account to analyze the possible locations of the host of the tags. For example, by analyzing the density of tags in an area, approximate length of the guardrails can be estimated. Tags with buffers are represented in the BIM model; (4) The tags together with the structure models are export to Navisworks, which is a powerful tool for 4D simulation and conflict detection. By integrating the schedule, the current situation of the building is known by assuming that there is no big difference between the as-planned and as-built models. Plug-in is developed to incorporate rules to evaluate the risks of the space in the BIM model.

5. CASE STUDY

5.1 RFID Tests

A fixed reader ($1,250) is used to collect data from 18 passive tags ($10) and 18 active tags ($10), which are placed to form a 6×6 grid, with a 2-meter gap between two tags, as shown in Fig. 7(a). Two concrete columns are within the area. The fixed reader is placed at different locations and orientations to test the visibility of the tags (Fig. 7(b) (c) (d)). Data are collected for duration of 10 min with a reading interval of 30 seconds. The visibility of each tag is highlighted in the three cases, which indicates a direct line-of-sight is essential for a good visibility. Relationship between the distance and the RSSI is investigated, as shown in Fig. 8. Active tags have a more steady relationship than that of passive tags. Within a range of 1.5 meters, distance can be described in a good accuracy.

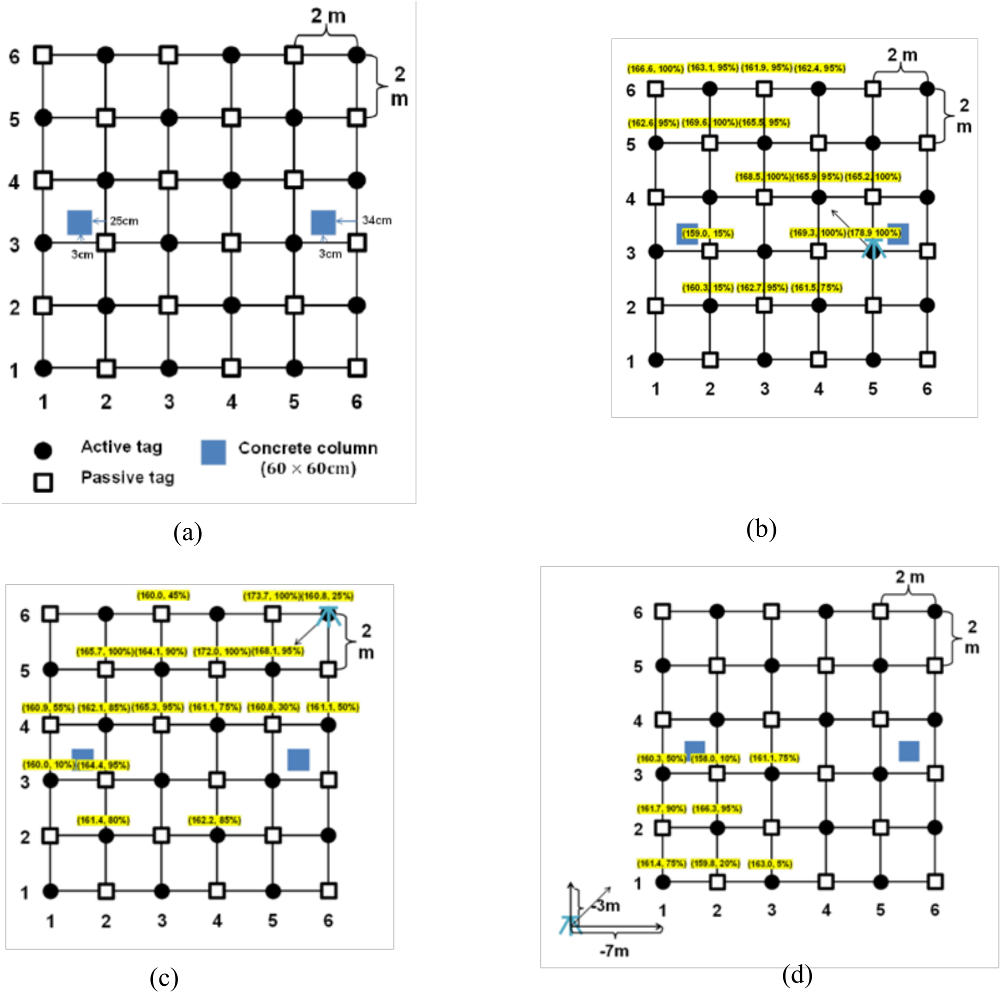


Fig. 7: Tag grid for visibility test

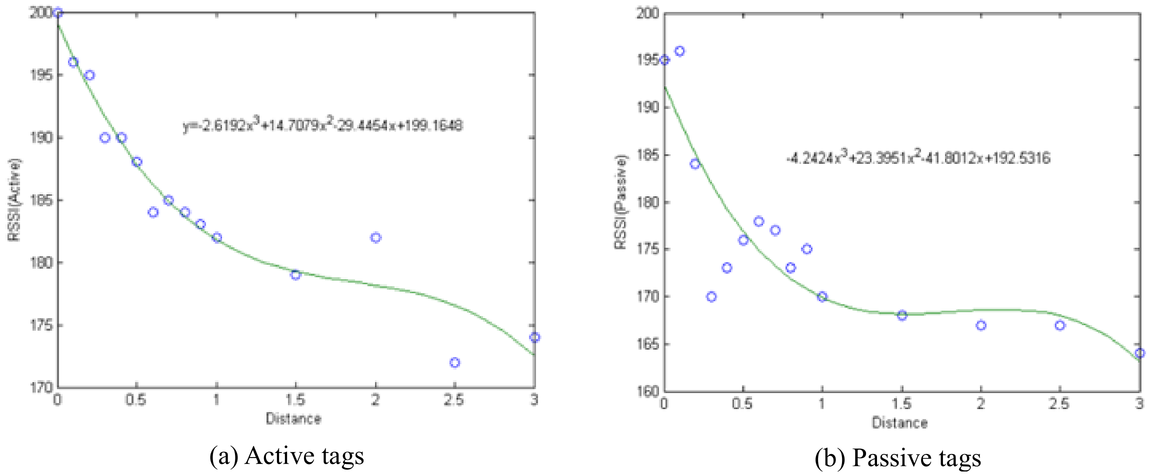
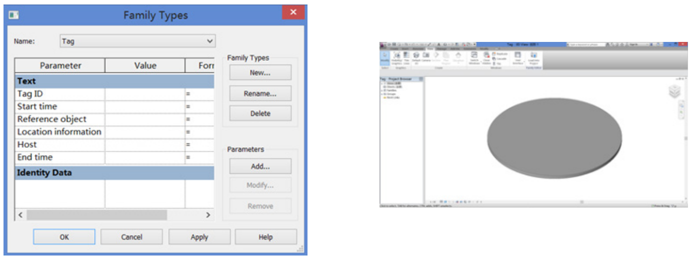


Fig. 8: Approximate relationship between RSSI and distance

5.2 BIM with Tags

A new object family is created to represent tags in the BIM model, as shown in Fig. 9(a). Tag ID, Location, Reference object, Host, etc. are stored in the property. Those data can be updated automatically or modified manually based on different user requirements. Fig. 9(b) shows the shape used for tag representation in the BIM model. Each RFID read-and-write (RW) tag can store 4KB data, where information including the tag ID, reference objects, etc., can be written to the memory at any stage of the construction. That information will be read and saved to the *Property* of each tag after the tag is detected on site. In addition, once the information in the *Property* of each tag is updated, the same information can be written to the memory of the RFID tag as well.



(a) (b)

Fig. 9: Tag registration in BIM

6. DISCUSSION

This paper describes an approach for building a spatial network by integrating RFID and BIM. Details are shown in the methodology of how to define spatial requirements for safety and facilities management, how to design permanent and temporary tags, how to define and identify space in BIM model, and how to automatically assess risks associated with workspaces. Some lab tests have been done to investigate the property of the RFID system selected for this research. However, more work should be done in the near future to get more solid linkage between RFID and BIM. A case study applied to real construction should be also carried out to investigate the feasibility, the scale, and the cost of the proposed approach.

7. REFERENCES

Eastman, C.M. and Eastman C. (2008). BIM handbook: a guide to building information modeling for owners, managers, designers, engineers, and contractors, John Wiley and Sons.

Fullerton, C. E., Allread, B. S., and Teizer, J. (2009). Pro-active-real-time personnel warning system. In: Construction Research Congress, Seattle, Washington, U.S.

Furlani K.M. and Pfeffer L.E. (2000). Automated tracking of structural steel members at the construction site, Proceedings ISARC '00, IAARC, Taipei, 1201-1206.

Ghanem A.G. and AbdelRazig Y. A. (2006). A framework for real-time construction project progress tracking, Earth and Space 2006, (188)112.

Giretti, A., Carbonari, A., Naticchia, B., and Grassi, M.D. (2009). Design and first development of an automated real-time safety management system for construction sites. J. of Civil Eng. and Management, ASCE, 15(4), 325-336.

Goodrum, P. M., McLaren, M. A. and Durfee, A. (2006). The application of active radio frequency identification technology for tool tracking on construction job sites, Automation in Construction, 15(3), 292-302.

Hammad, A., Asen, Y., and Zhang, C. (2011). Visualizing construction processes using augmented reality: fusing BIM, video monitoring and location information, the 11th International Conference on Construction Applications of Virtual Reality, November 2011, Weimar, Germany.

Hammad, A., Zhang C., Setayeshgar S. and Asen Y. (2012). Automatic generation of dynamic virtual fences as part of prevention program for construction safety, Proceedings of the 2012 winter simulation conference, Berlin, Germany.

Huang, X., and Hinze, J. (2003). Analysis of construction worker fall accidents. Journal of Construction Engineering and Management, ASCE, 129(3), 262-271.

Kiviniemi, M., Sulankivi, K., Kahkonen, K., Makele, T., and Merivirta, M.L. (2011). BIM-based safety management and communication for building construction, VTT research notes 2597.

Lee, H.S., Lee, K.P., Park, M., Baek, Y., and Lee, S.H. (2012). RFID-based real-time locating system for construction safety management, Journal of Computing in Civil Engineering, 26(3), 366-377.

Motamedi, A. and Hammad, A. (2009). Lifecycle management of facilities components using radio frequency Identification and building information model, Journal of Information Technology in Construction, Special issue on Next Generation Construction IT, 238-262.

Pradhan, A., Ergen, E., and Akinci, B. (2009). Technological assessment of radio frequency identification for indoor localization, Journal of Computing in Civil Engineering, ASCE, 23(4):230-238.

Song J., Haas C.T., Caldas C. and Liapi K. (2005). Locating materials on construction site using proximity techniques, Construction Research Congress, April 5-7, San Diego, US, 552-557.

Song J., Haas C.T., and Caldas C.H. (2006). A proximity-based method for locating RFID tagged objects, Advanced Engineering Informatics, 21: 367-376.

Taneja, S., Akcamete, A., Akinci, B., Garrett, J.H., Soibelman, L., and East, E.W. (2012). Analysis of three indoor localization technologies for supporting operations and maintenance field tasks, Journal of Computing in Civil Engineering, ASCE, 26(6), 708-719.

Torrent, G.D., and Caldas, H.C. (2009). Methodology for automating the identification and localization of construction components on industrial project, Journal of Computing in Civil Engineering, ASCE, 23(1), 3-13.

Zhang, C., and Hammad, A. (2012). Multiagent approach for real-time collision avoidance and path re-planning for cranes, Journal of Computing in Civil Engineering, ASCE, 26(6).

Zhang, C., Hammad, A., and AlBahnassi, H. (2009). Collaborative multi-agent systems for construction equipment based on real-time field data capturing, ITcon Vol. 14, Special Issues on Next Generation Construction IT: Technology Foresight, Future Studies, Roadmapping, and Scenario Planning, 204-228.

Zhang, C., Hammad, A., and Rodriguez, S. (2012). Crane pose estimation using UWB real-time location system, Journal of Computing in Civil Engineering, ASCE, 26(5):625-637.

Zhang, C., Hammad, A., Soltani, M.M. and Setayeshgar, S. (2012). Dynamic virtual fences for improving workers safety using BIM and RTLS, the 14th International Conference on Computing in Civil and Building Engineering, ICCCBE, June 2012, Moscow, Russia.

IMPROVING SOPHISTICATION AND REPRESENTATION OF SKILLED LABOR SCHEDULES ON PLANT SHUTDOWN AND MAINTENANCE PROJECTS

Ming-Fung Francis Siu, Ming Lu, Simaan AbouRizk
Department of Civil & Environmental Engineering, The University of Alberta, Edmonton, Alberta, Canada

Vincent Tidder
KBR of Turnarounds, KBR Industrial Canada Ltd

ABSTRACT: *Plant shutdown and maintenance, commonly termed as the turnaround project in the industry, aims to ensure safe and reliable production of an existing oil refinery and to expand capacities of existing plant facilities. Subject to constraints such as fixed project period, limited total budget, earliest activity start times, confined working areas and emerging events and found work during project execution, it is challenging to make, track and update detailed hour-by-hour turnaround schedules so as to effectively allocate specialist trades and skilled laborers. The ultimate goal is to complete the turnaround in a fixed time window and bring plant production back on line. Different from common construction project schedules, activity definitions, logical relationships and resources availabilities constantly change. The existing project scheduling methodology and tools are not sufficient or capable to cope with turnaround scheduling. This paper is intended to reveal the complexities of a typical turnaround project. A new methodology framework is proposed to plan resource-constrained, location-based turnaround activities. An in-house developed simulation-based scheduling tool is further employed to generate detailed resource allocation plans, factoring in resource availability limits and shift calendar constraints. The resource configurations can be further optimized, resulting in the shortest total project duration. In conclusion, this research has led to significant improvements on sophistication and representation of skilled labor schedules critical to effective planning and control of turnaround projects.*

KEYWORDS: *Shutdown, Maintenance, Turnaround, Scheduling, Optimization, Resource Allocation, Resource Calendars, Resource Shifts, Resource Breaks, Visualization.*

1. INTRODUCTION

Industrial construction develops and maintains oil and gas process plants. Such projects commonly feature installation of prefabricated modules and involve labor-intensive installation tasks completed by specialist trades. Similar to precast construction, prefabricated modules are shipped and assembled on the industrial site. This can greatly reduce the project time for building a new plant or upgrading an existing one. Song et al. (2005) surveyed construction practitioners to evaluate the feasibility of implementing pre-fabrication, pre-assembly, modularization and off-site fabrication. They concluded that implementation of these processes potentially shortens the project duration and is particularly suitable for executing plant shutdowns, outages or turnarounds; moving labor-intensive jobs to locations with adequate skilled labors eases labor resource shortage on site.

Plant shutdown and maintenance, commonly termed as the *turnaround project* in the industry, aims to expand the current production capacity and maintain the plant reliability during normal plant operations. Previous industrial-construction related research has investigated labor productivity (Lemna 1986; Lu et al. 2000; AbouRizk et al. 2001), access road planning (Varghese and O'Connor 1995), process simulation (Azimi et al. 2010; Taghaddos et al. 2010), tracking resource using bar code (Bell and McCullouch 1988), robotic total station and photogrammetry (Siu et al. 2013). In the present research, we address the challenge of making, tracking and updating detailed hour-by-hour turnaround schedules, so as to effectively allocate specialist trades and skilled laborers to complete the turnaround just on time. Turnaround schedule is subjected to constraints such as fixed project period, limited total budget, earliest activity start times, crowded working areas and emerging events and found works during project execution.

Citation: Siu, M-. F. F., Lu, M., AbouRizk, S. & Tidder, V. (2013). Improving sophistication and representation of skilled labor schedules on plant shutdown and maintenance projects. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Georgy et al. (2000) studied data from the US construction industry and concluded that the schedule performance indexes for 42 projects were between 102.9% and 123.2%, implying that most industrial projects would incur delays against as-planned schedules. They also reported that there were 43% project scope changes during the construction phase. The associated re-work (re-fabrication) was identified as one major factor for schedule delay and cost overrun. O'Connor and Tucker (1986) conducted a questionnaire survey for an industrial upgrading plant project and positively correlated constructability improvement to effectiveness in design communication. The schedule is vital to estimate and communicate man-hour consumed, budget cost and available time of limited resources. Critical path method (CPM) is the de-facto technique to schedule industrial construction and turnaround projects. However, CPM is not sufficient to account for turnaround-specific project factors, including (1) turnaround activities are planned on an hourly basis; (2) limited labor resources in turnaround are specialist trades, who perform specific tasks with special permit and license, work 24 hours in multiple shifts; (3) resource provision limits are highly constrained by space and normally vary in different time periods (e.g. during day and night shifts).

The contractor is often pressed to deliver the plant upgrade and maintenance project within a short period of time. Pushing back the plant start-up date by one day can lead to substantial economic losses. To tackle limitations of CPM in planning industrial projects, Siddiqui and Rafiuddin (2012) proposed a flow-line method based on linear scheduling to maintain resource continuity in repetitive industrial projects. They argued that the existing CPM method is not suitable because its incapability to visualize resource spatial conflict and continuous workflow requirements. Recent turnaround scheduling research efforts by Coughlan et al. (2010) and Rieck et al. (2012) proposed the use of mathematical programming to level resources. However, the large quantity of resource induced constraints in a realistic turnaround case may prevent the generation of a feasible solution within a reasonable amount of time. In contrast, the research described in this study sheds light on the importance of location-based resource allocation in turnaround scheduling, subject to field breaks during day and night shifts. The optimization technique is further employed to schedule activities under project constraints, thereby minimizing project duration and project cost.

In this paper, fundamentals of a typical oil refinery plant are first introduced, followed by elucidating on potential challenges in managing industrial construction projects by applying existing workflow tracking and scheduling techniques. A methodology framework is proposed to enhance the schedule management, so as to more effectively manage a resource-constrained, location-based turnaround project. A three-week turnaround project case study is included to illustrate project complexity and demonstrate method application. An in-house developed scheduling tool, named as *Simplified Simulation-based Scheduling* (*S3*) (Lu et al. 2008), is used to generate and optimize the resource allocation plan. Conclusions are drawn by discussing some on-going research in regards to multiple shift resource quantifications, resource-constrained time-cost integrated analysis, and photo-based 3D modeling, all intended to assist in critical decision making processes in scheduling turnaround projects.

2. INDUSTRIAL REFINERY PLANT FUNDAMENTALS

An oil and gas refinery plant is typically composed of a generator and a reactor as shown in Fig. 1(a). Through the introduction of catalyst, chemical reactions take place in the cyclones installed inside the regenerator and the reactor heads, which turn heavy oil (petroleum crude) to light oil (gasoline). The crude first enters the riser at the base to blend with the catalyst stored inside the regenerator. As oil vaporizes, catalytic cracking reactions take place. The hydrocarbons break down into smaller molecules. The vaporized hydrocarbons mixed with catalyst flow into the reactor. The main function of the reactor is therefore to segregate the mixture of hydrocarbon and catalyst into two separated portions. The primary cyclones are connected to the central riser. Through the primary and secondary cyclones (Fig. 1(b)) in the reactor, the catalyst and the cracked hydrocarbon are separated before the catalyst flows back to the regenerator. Some by-products, such as coke, deposit on the surface of catalyst and reduce catalyst reusability. The cyclones collect and return the catalyst to the stripper through trickle valves. The hydrocarbon products flow out from the top of the regenerator and into the fractionator for further light oil separation. Meanwhile, the catalyst flows back to the regenerator at the bottom through a slide valve; at the same time, the oxygen-rich air is induced for coke combustion in the regenerator cyclones. For a more detailed depiction of chemical reactions, readers can refer to Sadeghbeigi (2012).

The workers usually work inside the regenerator and the reactor. The working space is categorized as confined space − a restricted space which may become hazardous to a worker entering it due to the following considerations: (i) the atmosphere can be dangerous or injurious (such as oxygen deficiency or enrichment, flammability, explosivity or toxicity); (ii) the changing circumstances within the space that present a potential for injury or illness; or (iii) the inherent characteristics of an activity can produce adverse or harmful consequences within the space (OSSA 2013). Therefore, during schedule planning and updating stages, the schedulers and planners must be aware of the maximum quantities of laborers that are allowed to enter certain restricted locations at one time.

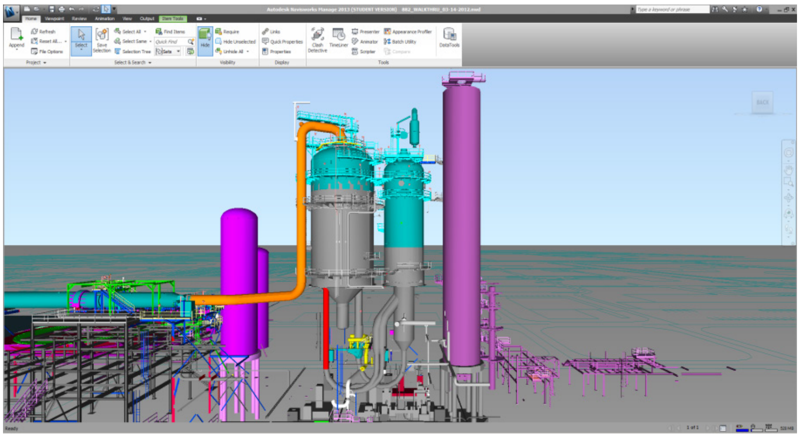


Fig. 1(a): Typical oil refinery plant site layout overview

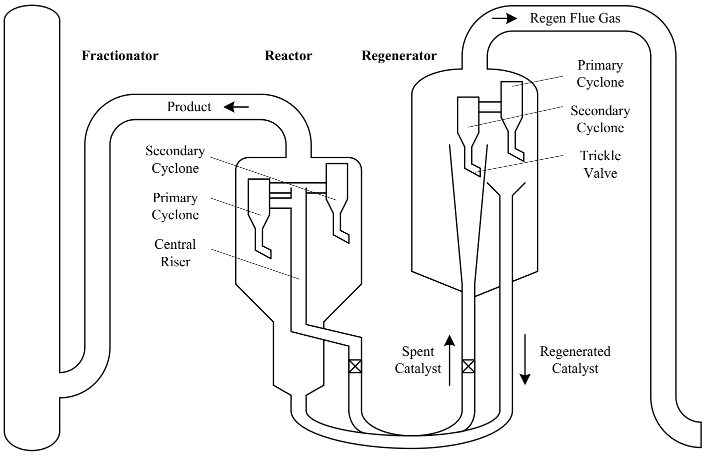


Fig. 1(b): Components and chemical flows inside the reactor and regenerator

3. COMPLEXITIES IN MANAGING TURNAROUND PROJECT SCHEDULES

The turnaround project is composed of three phases: pre-turnaround; turnaround; and post-turnaround. The scope of pre-turnaround is limited to planning temporary structure assembly, material logistics and quality assurance. The plant shuts down during the turnaround period. Plant components are removed, upgraded and repaired. The temporary structures are removed, the old structures are disposed of, and the upgraded plant starts up.

Subject to the contractually stipulated plant shutdown and startup dates, the turnaround is generally expected to complete within the tight time period without any delay. Although a detailed turnaround schedule (baseline schedule at T_0) is prepared, the work scope is partially unknown until the plant is shut down and examined. The existing vessels are opened up for quality inspections. Any existing structure is scrutinized and additional activities can be added to the baseline schedule. The superintendents usually record activity progress by using time-stamped photos. One example is given as of crane lifting sequences shown in Figs. 2(a) to 2(c). The photos capture the crane lifting sequence during the turnaround of the refinery under scrutiny. The actual start and finish times of the activities were tracked in the field.

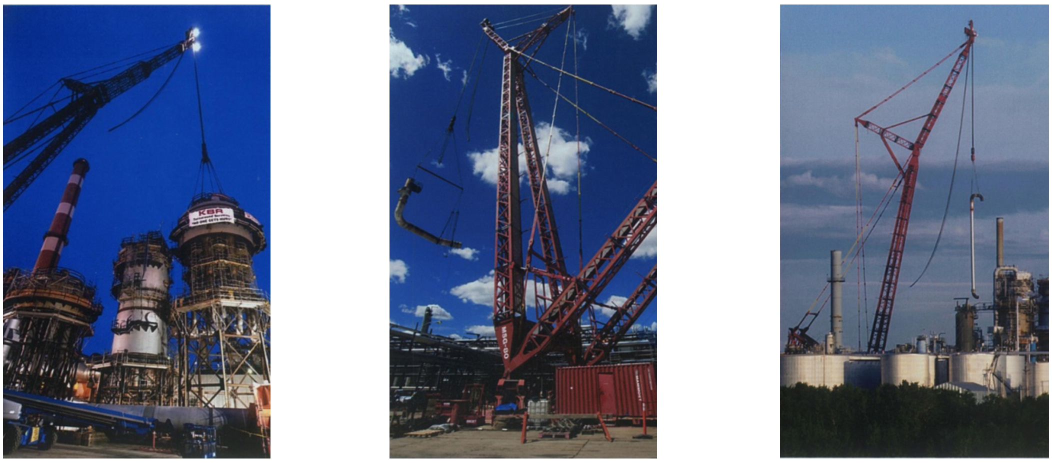


Fig. 2(a): Reactor lifting Fig. 2(b): Pipe 1 lifting Fig. 2(c): Pipe 2 lifting

It presents distinctive challenges for schedulers to track and update the *as-planned schedule* while also coping with emerging events and found works during the turnaround stage. The inter-activity logical relationships are frequently revised during project execution. Note such frequent logic change rarely occurs on building and civil projects, but remains common practice to dynamic turnaround projects. Fig. 3 shows the typical workflow in maintaining turnaround schedules.

The superintendents report the work done during the previous period (day) in the site progress meeting, with the aid of field photos. The schedulers record the completed work, new found work, and expected emerging work based on the as-planned work schedule at T_0. This *newly created as-planned schedule* provides the baseline schedule generated at T_1 as the basis for the next schedule update cycle. In the meantime, the labor resource productivity performances are evaluated. Project management is alerted if labor performance decreases sharply.

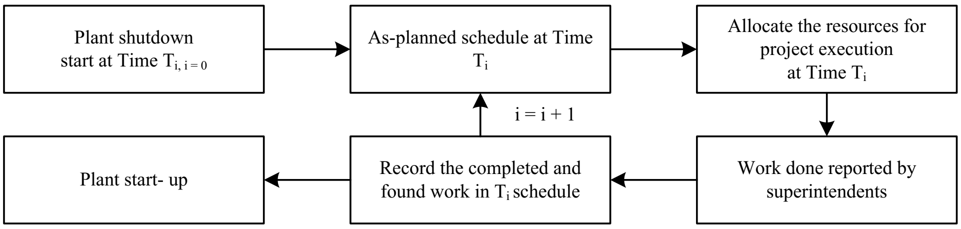


Fig. 3: Work sequence in maintaining a turnaround schedule

Schedule changes are inevitable and some activities may have to relocate to another area, some are irrelevant and removed, while others are newly defined. The schedulers add or remove activities to the schedule and place the week number in the customized column *added work* in the schedule to highlight the changes made for record keeping proposes. Despite the visualization power of advanced 3D plant design software to accurately communicate the actual design to the client (O'Connor and Tucker 1986), the field-level communication largely relies on the 2D drawings, pictures, and the project schedule. Additionally, an accurate and precise turnaround schedule is required to provide the baseline for assessing labor productivity performances.

An updated, valid turnaround schedule is also conducive to resource allocation for jobs to be started, especially allocation of limited, highly specialist trades with multiple shifts and field breaks. The commonly-used scheduling tool, *Primavera P6*, can generate a feasible schedule to cope with labor resources constraints. Nonetheless, this tool can only provide a Gantt chart for scheduled activities, but fail to visualize the work assigned to each individual resource, or determine the optimum quantities of workers as-needed in the field, or account for multiple shifts with field breaks.

In practice, the quantities of skilled laborers as needed are solely estimated based on experiences of the schedulers and managers. The resource leveling function of Primavera P6 simply ignores most resource constraints (such as commonly used activity type of *task-dependent* in Primavera P6) (Siu 2011; Harris 2012). As a result, the Primavera P6 scheduled working hours are solely dependent on activity calendars, regardless of resource availability and calendars being applied. Hence, a valid and detailed resource allocation plan cannot be generated by Primavera P6.

4. METHODOLOGY FRAMEWORK

To improve the current practice of turnaround project scheduling in a resource-constrained, location-based context, a new methodology framework is proposed (Fig. 4). The work breakdown structure is first developed based on the locations of the site. Activities under the same work package are technologically linked to form a local project network. At time T_i, the schedule is updated by incorporating completed and newly defined emerging activities into the as-planned baseline schedule (Fig. 3). Then, activity and resource constraints, including resource availability limits and resource multiple shift calendars with field breaks, are identified. These constraints are imposed to the scheduling-simulation model for analysis in a simulation platform. The resource-constrained schedule is generated in a relatively short time compared with mathematical programming. The above procedures are executed immediately after each turnaround progress meeting. A detailed resource allocation plan showing activity start and finish times, resource allocation details, resource breaks and idling times can be generated for visualization and communication purposes. The schedule can be further optimized by identifying the shortest project duration or the lowest project cost, along with the optimum quantities of resources to employ in the field. The improved schedule presentation can effectively guide the execution of the work flow of each trade or each individual in specific areas on a turnaround site, as illustrated with a practical case study in the ensuing section.

5. INDUSTRIAL TURNAROUND PROJECT CASE STUDY

A three-month industrial turnaround project was executed in Alberta, Canada in May to August, 2012. The project is to upgrade the existing oil refinery facilities including the reactor, regenerator, and the overhead system. Fig. 5 depicts the overall scope of work, including the temporary and permanent structures. The scope for the present case study is narrowed down to the *reactor work package* during the turnaround execution. The work content consists of (1) replacing the four elbows in the reactor; (2) removing the existing head and cyclone assemblies; (3) installing new head and cyclone assemblies; and (4) completing refractory and tie in electrical instrumentation, piping and platforming. As per contractual stipulations, the contractor reported progress achieved on activities on a shift-by-shift basis during the turnaround execution. A three-week schedule was updated on a daily basis.

The project definitions, including activity name, duration, shifts, technological relationships, and resource requirements are tabulated in Table 1. There are totally 109 activities planned for approximately three weeks (only 10 activities are given in Table 1 owing to the paper size limit). The quantities of different skilled laborers required by each activity are given in brackets in the column *resources* of Table 1. The shift calendars are summarized in Table 2. Regardless of day or night shift, labor resources work on an hourly basis. For example, calendar 2×12×7 denotes laborers run on 2 shifts per day, each shift is 12 hours, and each week has 7 work days.

In the current practice, the 2×12×7 shift calendar is commonly applied to schedule turnaround specialist trades, with hourly labor rates doubled for night shift. Production rates (productivity) for day-shift and night-shift crews are generally assumed identical. Figs. 6(a) and 6(b) show the working hour settings in the Primavera P6 based turnaround schedule. It implies one resource type is only associated with one applicable shift calendar while Primavera P6 is not able to distinguish day or night shifts. It is noteworthy that accounting for differences in productivity performance and the effects of varying crew sizes during day shift and night shift are not of the scope of this paper.

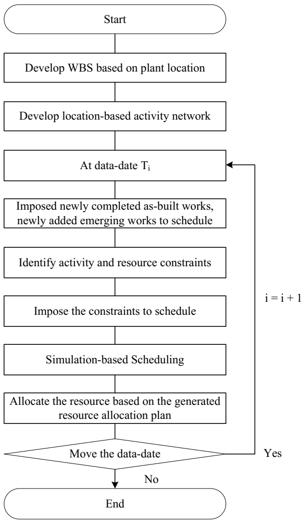


Fig. 4: Methodology flowchart

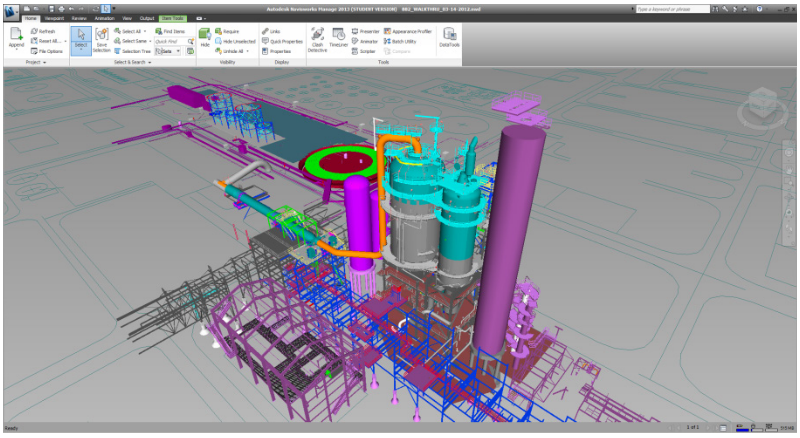


Fig. 5: Overall scope of the plant upgrading project

Table 1: Activity requirements

No	ID	Activity Name	Dur	Shift	Suc	Resources
1	A192440	Install hex on external riser at cut line. Approx. 30 sq. ft.	50h	2x10x7	A190430	KBR Boilermaker Welder[2] KBR Boilermaker [2]
2	A189340	Pre job meeting to install new Reactor head	1h	2x10x7	A193000	KBR MSG80 3600 ton[1] KBR Rigger[6]
3	A193000	Position crane and install rigging on new head	8h	2x10x7	A193010	KBR MSG80 3600 ton[1] KBR Rigger[6]
4	A193010	Lift new head and swing Amine unit	4h	2x10x7	A189400	KBR MSG80 3600 ton[1] KBR Rigger[6]
5	A189350	Remove Rigging and boom clear of work area	4h	2x10x7	A190490, A189410, A209280	KBR MSG80 3600 ton[1] KBR Rigger[6]
6	A189400	Continue swing and lower new Reactor head onto shell	5h	2x10x7	A189350	KBR MSG80 3600 ton[1] KBR Rigger[6]
7	A190490	Hoard in decking on lower dipleg bracing back to shell	10h	2x10x7	A190270	KBR Scaffolder[6]
8	A189410	Fit and Tack New head to Existing Reactor Shell	20h	2x10x7	A189420	KBR Boilermaker Welder[4] KBR Boilermaker[4]
9	A209240	Install landing from stairway to RX Platform 0	10h	2x10x7	A209250	KBR Iron Worker[3] Sterling-130 Ton Crane[5]
			…			
109	A209310	Install Platform 3, Section 0-90 from RX to Reg.	30h	1x10x4	-	KBR Boilermaker[3] KBR Boilermaker Welder[1] Sterling-130 Ton Crane[1]

Table 2: Shift calendars

Name	Weekly working hours		Name	Weekly working hours		Name	Weekly working hours	
1×10×4	Mon-Thur	10 hrs/day		Mon	15 hrs/day	7×24	Mon-Sun	24 hrs/day
1×10×5	Mon-Fri	10 hrs/day	2×10×6	Tue-Sat	20 hrs/day	7×10×2	Mon-Sun	24 hrs/day
1×10×6	Mon-Sat	10 hrs/day		Sun	6 hrs/day			
1×10×7	Mon-Sun	10 hrs/day	2×10×7	Mon-Sun	20 hrs/day			
1×12×7	Mon- Sun	10 hrs/day	2×12×7	Mon-Sun	24 hrs/day			
1×10×6	Mon-Sat	10 hrs/day						

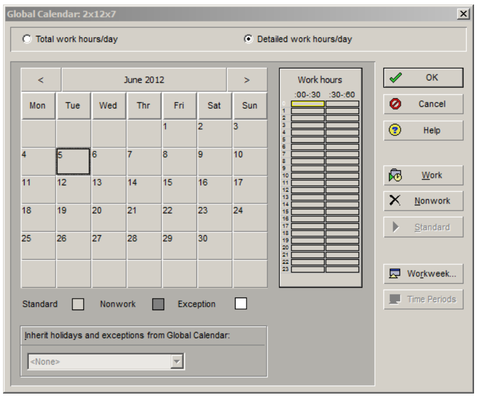


Fig. 6(a): 2×12×7 shift calendar

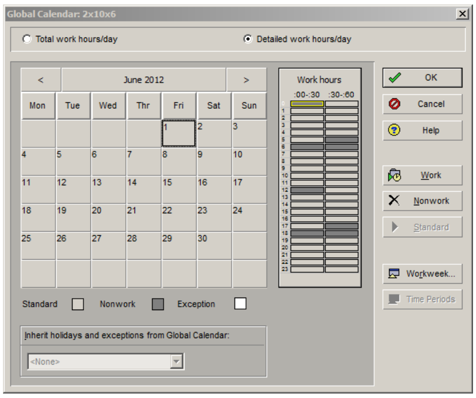


Fig. 6(b): 2×12×6 shift calendar

Table 3: Specialty trade resources

Resource Name	Calendar	Max Units/Time
IOL Complex Process Operator	2x12x7	1
IOL Inspection	2x10x6	1
IOL Supervisor	2x12x7	1
IOL Technical	2x10x6	1
KBR Boilermaker	1x10x6	10
KBR Boilermaker Welder	1x10x6	10
KBR Inspector	1x10x6	1
KBR Iron Worker	1x10x6	5
KBR Liquid Penetrant Inspection	2x12x7	1
KBR MSG80 3600 ton	2x12x7	1
KBR Painter	2x12x7	2
KBR PAUT Inspection	1x10x6	1
KBR Pipefitter	1x10x6	2
KBR Pipefitter Welder	1x10x6	1
KBR Rigger	1x10x6	6
KBR Scaffolder	1x10x6	6
KBR X-Ray	1x10x6	1
Refractory	2x12x7	10
Sterling-130 Ton Crane	2x12x7	5

In this case study, an in-house developed scheduling tool, named as *Simplified Simulation-based Scheduling* (*S3*), was used to schedule and optimize the complicated activity and resource work flows. In previous research, the tool was successfully applied to (1) optimize the resource provisions and activity schedule on a box culvert construction project (Lu et al. 2008) and (2) conduct delay analysis based on resource-constrained schedule (Siu and Lu 2011). Herein, assumptions underlying the simulation-based scheduling model are listed as follows:

- The resources assigned to each activity are engaged at the activity start time, when the budgeted man-hours are consumed as a result. Contrasted with the *task-dependent* activity type in Primavera P6, *resource-meeting* or resource matching on activities are applied which is relevant to resource-constrained construction scheduling. S3 adopts fixed-duration approach to allow users to enter the fixed length of work duration. In the current case study, the activity duration originally defined in the Primavera P6 schedule is directly exported as the fixed duration for S3 scheduling analysis.
- The *maximum unit per time unit* is estimated based on the minimum resource quantities required to execute the reactor works on one shift. For this reactor work package, Table 3 shows the maximum limits available for different trades or laborers involved in one shift.
- The start times set for certain activities are taken as *must start on or after* constraints. For example, one activity is technologically linked to other work packages, or depends on required material and equipment resources delivered to site on specific dates, or availabilities of space resources. The date and time of those constraints are exported from the existing Primavera P6 schedule as shown in Table 4. The value of time point represents the hours after the project start time (16-Jun-12 00:00).

Table 4: Start time constraints

ID	Activity	Time Point	Date	Time
3	A189340	64	18-Jun-12	16:00
10	A209240	81	19-Jun-12	09:00
12	A201270	88	19-Jun-12	16:00
78	A189720	265	27-Jun-12	01:00
94	A201160	332	29-Jun-12	20:00
95	A201180	332	29-Jun-12	20:00
96	A201200	332	29-Jun-12	20:00
102	A202480	357	30-Jun-12	21:00
103	A189730	357	30-Jun-12	21:00

5.1 Resource Allocation Plan Visualization

Fig. 7 depicts the zoom-in view of the obtained *boilermaker* allocation plan from time points 137 to 151. The horizontal axis represents the time line from time 0 (project start hour) to 759 (project end hour). The highlighted grey color indicates the resource breaks. The colored bars denote the work assigned to each individual boilermaker. The event list was also generated (Table 5). In addition to the Gantt chart visualization, the improved representation of skilled labor allocation plan accounts for the field breaks on an individual-laborer level. This lends itself to assisting the schedulers in assigning jobs and communicating to the crews in a straightforward way.

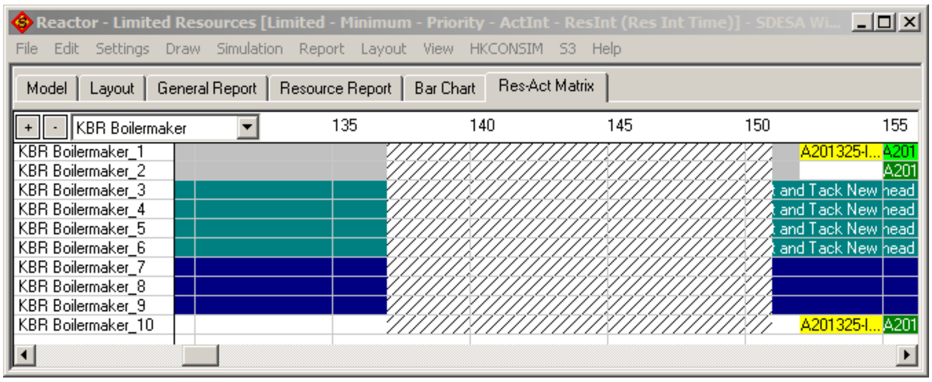


Fig. 7: Resource allocation plan (zoom-in view)

Table 5: Event list from time points 137 to 151

Time Point	Time	Boilermaker ID	Activities
130-137	21-Jun-2012 10:00 to 21-Jun-2012 17:00	1, 2	A192440
		3, 4, 5, 6	A189410
		7, 8, 9	A209280
		10	Idle
137-151	21-Jun-2012 17:00 to 22-Jun-2012 07:00	1, 2, 3, 4, 5, 6, 7, 8, 9	Break
151-152	22-Jun-2012 07:00 to 22-Jun-2012 08:00	1, 2	A192440
		10	(Idle)
151-155	22-Jun-2012 07:00 to 22-Jun-2012 11:00	3, 4, 5, 6	A189410
		7, 8, 9	A209280
152-155	22-Jun-2012 08:00 to 22-Jun-2012 11:00	1, 10	A201325
		2	Idle

5.2 Optimization

The turnaround schedule can be further enhanced by optimizing resource configurations, namely: finding the best combination of the quantities for different skilled laborers on a shift so as to reduce resource idle time and shorten total project duration. S3 implements the particle swarm optimization (PSO) algorithm to seek optimal schedule solutions. In this case, the objective function is set to minimize the project completion time. The simulated schedules before and after the optimization are shown in Figs. 8(a) and 8(b), respectively. The project end time are considerably shortened from 759 to 663 hours. Figs. 8(c) and 8(d) show the resource allocation plans of *boilermaker welder*, *technical* and *complex process operator*. The break patterns for different specialist trades are identical after the optimization.

Table 6 contrasts the resource quantities before and after the optimization analysis. The optimum resource quantities for this case are determined as: 12 *boilermaker welders* (increased from 10 to 12); 20 *boilermakers* (increased from 10 to 20); 10 *riggers* (increased from 6 to 10); 3 *pipefitters* (increased from 2 to 3); and 4 *iron workers* (reduced from 5 to 4). In the original experience-based resource limits setting, the skilled laborer resources were mostly undersupplied. It should be pointed out that after optimization, two independent activities can be scheduled in the same time period and at the same location. Safety or space constraints may prevent the concurrent execution of the two activities. Particular safety measures must be taken or additional precedence relationship must be imposed between them. For instance, the scaffolders working overhead may accidentally drop down tools to the boilermakers' work area; as such, if the two activities are scheduled to concur in the field, a protective net will be installed to provide adequate protection for the boilermakers.

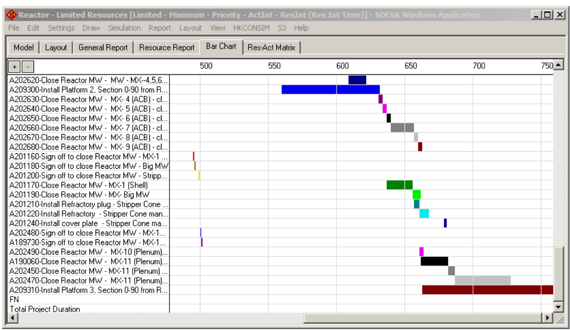


Fig. 8(a): Resource schedule

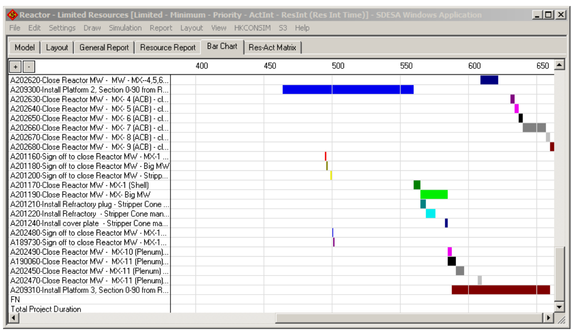


Fig. 8(b): Optimized resource schedule

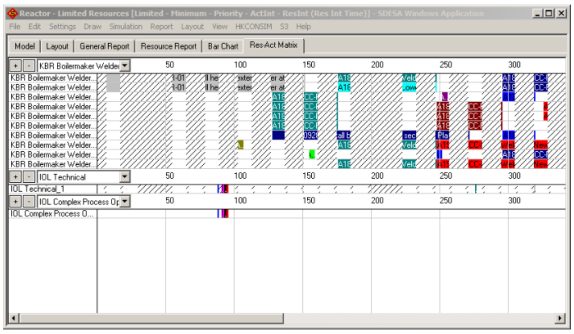


Fig. 8(c): Resource allocation plan

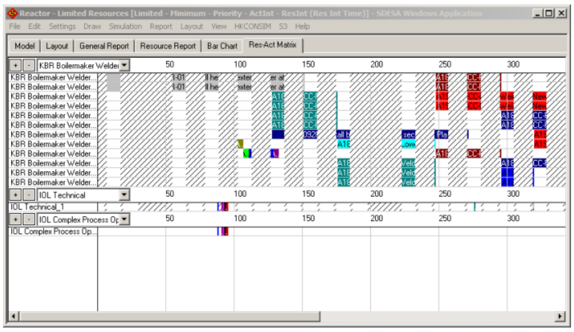


Fig. 8(d): Optimized resource allocation plan

Table 6: Resource provisions before and after optimization

	Before Optimization	After Optimization
KBR Boilermaker Welder	10	12
KBR Boilermaker	10	20
KBR MSG80 3600 ton	1	1
KBR Rigger	6	10
KBR Scaffolder	6	6
KBR Iron Worker	5	4
Sterling-130 Ton Crane	5	5
IOL Technical	1	1
IOL Inspection	1	1
IOL Complex Process Operator	1	1
Refractory	10	10
KBR Pipefitter	2	3
KBR Pipefitter Welder	1	1
KBR Liquid Penetrant Inspection	1	1
KBR Inspector	1	1
IOL Supervisor	1	1
KBR X-Ray	1	1
KBR PAUT Inspection	1	1
KBR Painter	2	2

6. CONCLUSION

The industrial plant shutdown and maintenance turnaround project is difficult to schedule owing to dynamic and complex constraints. Commonly-used scheduling tools, such as *Primavera P6*, fail to generate valid, sufficient schedules to cope with the hour-by-hour resource calendars and labor resource availability limits. The traditional activity bar chart is not sufficient to convey the resource allocation to each skilled laborer resource at an individual level. In this paper, a real-world case study is conducted to illustrate complexities, current practices and limitations in planning turnaround projects. A methodology framework has been proposed to better manage turnaround schedules generation and optimization based on the in-house developed scheduling system of *Simplified Simulation-based Scheduling* (*S3*). As demonstrated by the case study, the resulting resource allocation plans improve the sophistication and representation of skill labor schedules for effectively controlling and communicating the planned workflows.

Further research will be conducted in regard to: (1) Analysis of varied resource limits in day and night shifts such that each resource type, for instance, *boilermaker*, is divided to *boilermaker day shift* and *boilermaker night shift* and the resource limit and break constraints are separately imposed. Further optimization will be useful to objectively estimate the *optimum* resource quantities for both day and night shifts. (2) Resource-constrained time-cost integrated analysis: changing resource provisions may affect both the budgeted cost and the project completion time. The turnaround schedulers make timely decisions in estimating the impact on the budget cost and project completion time of imposing different *resource-time* alternatives on activities. The resource-constrained time-cost integrated analysis will automatically identify the best alternatives at individual activity level and generate the most cost-effective resource-constrained schedule at the global project level. (3) Photo-based 3D modeling integration: the space constraints will be evaluated based on time-stamped photo-based 3D models to ensure safety and productivity in planning turnaround activities. For example, the quantities of laborers allowed to be present at specific work locations can be objectively determined based on the photogrammetric analysis. Hence, the space constraints will be directly integrated to the simulation-based scheduling models. Eventually, the planning and control of highly complicated and dynamic turnaround projects can be effectively managed, and project objectives with regards to safety, time, cost, quality can be achieved.

7. ACKNOWLEDGEMENT

The present research was substantially funded by National Science and Engineering Research Council (NSERC) and KBR Canada Ltd. The authors would like to acknowledge Hal Williams (Senior Vice President of Operations, KBR Canada) for sharing his knowledge and experience in managing industrial turnaround projects; Dan Pelchat (General Manager of Turnarounds, KBR Canada) for arranging for site office and transportation during turnaround project execution; Brett Matson (Previous Scheduler of Turnarounds, KBR Canada) for clarifying the current practice of scheduling turnaround projects.

8. REFERENCES

AbouRizk, S., Knowles, P. and Hermann, U. (2001). Estimating Labor Production Rates for Industrial Construction Activities, *Journal of Construction Engineering and Management*, 127(6), 502-511.

Azimi, R., Lee, S. and AbouRizk, S. M. (2010). Resource Performance Indicators in Controlling Industrial Steel Projects, *ASCE Construction Research Congress*, May 2010, Banff, Canada, 21-30.

Bell, L. C. and McCullouch, B. G. (1988). Bar Code Applications in Construction, *Journal of Construction Engineering and Management*, 114(2) 263-278.

Coughlan, E. T., Lübbecke, M. E. and Schulz, J. (2010). A Branch-and-Price Algorithm for Multi-Mode Resource Leveling. *Experimental Algorithms*. Springer Berlin Heidelberg, 226-238.

Georgy, M., Chang, L. and Walsh, K. (2000). Engineering Performance in Industrial Construction, *ASCE Construction Congress*, Orlando, Florida, United States, 917-927.

Harris, P. E. (2012). *Planning & Control Using Primavera P6 Version 7: For all industries including Versions 4 to 7*, Eastwood Harris Pty Ltd.

Lemna, G., Borcherding, J. and Tucker, R. (1986). Productive Foremen in Industrial Construction, *Journal of Construction Engineering and Management*, 112(2), 192-210.

Lu, M., and AbouRizk, S. and Hermann, U. (2000). Estimating Labor Productivity Using Probability Inference Neural Network, *Journal of Computing in Civil Engineering*, 14(4), 241-248.

Lu, M., Lam, H. C. and Dai, F. (2008). Resource-Constrained Critical Path Analysis based on Discrete Event Simulation and Particle Swarm Optimization, *Automation in Construction*, 17(6), 670-681.

O'Connor, J. and Tucker, R. (1986). Industrial Project Constructability Improvement. *Journal of Construction Engineering and Management*, 112(1), 69-82.

OSSA Oil Sands Safety Association (2013). *Confined Space Entry and Monitor Standard*, Oil Sands Safety Association, Alberta, Canada.

Rieck, J., Zimmermann, J. and Gather, T. (2012). Mixed-Integer Linear Programming for Resource Leveling Problems. *European Journal of Operational Research*, 221(1), 27-37.

Sadeghbeigi, Reza (2012). *Fluid Catalytic Cracking Handbook - An Expert Guide to the Practical Operation, Design, and Optimization of FCC Units*, Elsevier.

Siddiqui, M. and Rafiuddin, M. (2012). Identifying Scheduling Inefficiencies for Industrial Projects Using the Flowline View: A Case Study, *Computing in Civil Engineering*, 81-88.

Siu, M. F. (2011). *Study of Time Extensions and the Cost Implications in Construction Project Scheduling*, M.Phil. Thesis, Hong Kong Polytechnic University.

Siu, M. F. and Lu, M. (2011). Scheduling Simulation-Based Techniques for Earned Value Management on Resource-Constrained Schedules under Delayed Scenarios. *Proceedings of the 2011 Winter Simulation Conference*, Dec. 11–14, 2011, Phoenix, Arizona, USA, 3460-3471.

Siu, M. F., Lu, M. and AbouRizk, S. (2013). Combining Photogrammetry and Robotic Total Stations to Obtain Dimensional Measurements of Temporary Facilities in Construction Field. *International Journal of Visualization in Engineering*, Springer, 1(4), 1-15.

Song, J., Fagerlund, W., Haas, C., Tatum, C. and Vanegas, J. (2005). Considering Prework on Industrial Projects, *Journal of Construction Engineering and Management*, 131(6), 723-733.

Taghaddos, H., AbouRizk, S., Mohamed, Y. and Hermann, U. (2010). Simulation-Based Multiple Heavy Lift Planning in Industrial Construction, *Construction Research Congress* 2010, 349-358.

Varghese, K. and O'Connor, J. (1995). Routing Large Vehicles on Industrial Construction Sites, *Journal of Construction Engineering and Management*, 121(1), 1-12.

EFFECTIVENESS OF VISUAL FEATURES ON AS-BUILT BUILDING INDOOR ENVIRONMENTS MODELING

Zhenhua Zhu
Department of Building, Civil and Environmental Engineering, Concordia University, Montreal, Canada

ABSTRACT: *As-built information of building elements (e.g. element dimension, geometry, material, etc.) could be used to facilitate multiple building assessment and management tasks, including project progress monitoring, productivity analysis, construction inspection, etc. However, the current process for retrieving as-built information of building elements from remote sensing data is labor-intensive and time-consuming. This is especially true for modeling the building indoor environments prevalent with occlusions and partitions. In order to address these limitations, the use of RGB-D mapping has been proposed and shown a promise for modeling building indoor environments. One fundamental part in the RGB-D mapping is to select an appropriate combination of visual feature detectors and descriptors. This paper investigates the effectiveness of different visual feature detectors and descriptors on modeling 3D building scenes. Several visual feature detectors and descriptors (e.g. GFTT, SURF, SIFT, ORB, and BRISK) have been evaluated. The evaluation criteria considered in the paper include accuracy and speed. The feature detectors and descriptors have been tested in multiple building scenarios with the same hardware configuration. Based on the evaluation results, it could be found that the combination of a SURF feature detector and a BRISK feature descriptor is more accurate than the others. Meanwhile, the use of the ORB feature detector and descriptor could get the fast speed.*

KEYWORDS: *As-built building information, automation, comparative studies, RGB-D mapping*

1. INTRODUCTION

Three dimensional (3D) as-built information of building elements (e.g. columns, beams, and walls) record the actual status of buildings. Therefore, they have been identified useful for owners, designers, contractors, and facility managers in multiple building assessment and management tasks (Zhu, 2012). However, the current process of retrieving and modeling such information is labor intensive and time consuming. This is especially true in the case of building indoor environments. According to the report from a recent research study, a simple task for the generation of 3D point clouds for 40 rooms may require a 3D laser scanner to be set up at hundreds of locations due to potential indoor partitions and occlusions (Adan et al. 2011). Such labor-intensive and time-consuming nature significantly counteracts the benefits of using 3D as-built information in practice, unless the current information retrieval and modeling process can be improved, and the 3D as-built information could be updated and reviewed frequently (Pettee, 2005).

In order to reach this goal, several research studies have been proposed. Specific for the building indoor environments, the recent work built upon the RGB-D camera is promising. RGB-D stands for Red, Green, Blue plus Depth. Typically, an RGB-D camera, such as Microsoft© Kinect, is small, portable, and easy to carry, which makes it fit for the retrieval of as-built information in the building indoor environments. The camera could capture RGB-D images (i.e. pairs color and depth images simultaneously) almost in real time (30 Hz), and maintain the resolution of the images at 640x480. When an RGB-D image (i.e. a pair of the color images and depth images) is captured by the camera, a set of 3D points (i.e. point cloud) could be automatically generated. The point clouds from different RGB-D images could be further merged and aligned by being progressively mapped (i.e. RGB-D mapping).

Currently, there are many RGB-D mapping methods available (Henry et al. 2010; Engelhard et al. 2011). Their basic ideas are similar. First, the 3D point clouds are generated from the RGB-D images captured by the RGB-D camera. In the consecutive images, their visual features are detected, described, and matched. According the 2D matching results in the images, the corresponding matched 3D points in the point clouds are located. This way, the pair-wise transformation matrix between the point clouds could be estimated, and the point clouds could be registered under one 3D coordinate system. During the RGB-D mapping process, one of the critical steps lies in the

Citation: Zhu, Z. (2013). Effectiveness of visual features on as-built building indoor environments modelling. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

selection of appropriate combinations of visual feature detectors and descriptors for the detection, description, and matching of visual features.

The objective of this paper is to evaluate the effectiveness of different combinations of the visual feature detectors and descriptors in the RGB-D mapping process. In doing so, the framework following the basic RGB-D mapping idea has been implemented. The visual feature detectors and descriptors, including Good Features to Track (GFTT) (Shi and Tomasi, 1994), Features from Accelerated Segment Test (FAST) (Rosten and Drummond, 2006), Scale-Invariant Feature Transform (SIFT) (Lowe, 2004), Speed-Up Robust Features (SURF) (Bay et al. 2008), Oriented Fast and Rotated BRIEF (ORB) (Rublee et al. 2010), etc. have been considered. The different configurations of these visual feature detectors and descriptors have been tested in multiple building scenarios. The mapping accuracy and speed have been recorded. The evaluation results indicated that the combination of a SURF feature detector and a BRISK feature descriptor (i.e. SURF/BRISK) could reach the high mapping accuracy. The use of the ORB feature detector and ORB descriptor (ORB/ORB) could get the fastest mapping speed without the support of the graphic processing unit (GPU).

2. RELATED WORK

In general, visual features refer to those local points, blobs or regions of interest in a color (RGB) image. So far, several detectors and descriptors have been developed to distinctively detect and describe the visual features, even when the color images are under certain affine deformations. Here are the details of the common ones which have been widely used in computer vision applications.

2.1 Good Features to Track (GFTT)

In 1994, Shi and Tomasi (1994) presented the concept of GFTT. They designed a GFTT detector to decide which visual features were good for the purpose of visual tracking. In their work, the strong Harris corners (Harris and Stephens, 1988) with high eigen-values were first kept. Then, in the remaining corners, those that were relatively "weak" were further rejected, if there were relatively "strong" corners close to them. Consider the corners typically appear at object boundaries where multiple motions are highly possible. Therefore, the GFTT detector was expected to address the generalized aperture problem (Senst et al. 2012), and moreover the corners kept by the GFTT detector are always those whose motions can be reliably estimated.

2.2 Features from Accelerated Segment Test (FAST)

FAST was proposed by Rosten and Drummond (2006). Similar to the GFTT, it was designed based on a corner detector. The detection procedure for the FAST included two main steps. First, the potential corner points in an image were classified with a segment test. Then, a score value was calculated at each potential corner point. The score values could be used to remove the false corners that have been classified before. In general, the FAST detector (Rosten and Drummond, 2006) has been identified as reliable and fast (Rosten et al. 2010). Therefore, it has been widely used for the applications with the real-time requirements, such as Augmented Reality workspaces (Klein and Murray, 2007).

2.3 Binary Robust Invariant Scalable Keypoints (BRISK)

BRISK was proposed by Leutenegger et al. (2011). In their framework, a scale-space pyramid was first created by progressively half-sampling an original image. The potential regions of interest on each octave and intra-octave of the pyramid were then detected with the FAST detector (Rosten and Drummond, 2006). Then, the detection results were refined with the non-maxima suppression. Moreover, the BRISK feature descriptions were provided on the detection results using the configurable circular sampling patterns. In general, the BRISK detector and descriptor could produce both distinctive, scale and rotation invariant visual features.

2.4 Scale-Invariant Feature Transform (SIFT)

SIFT was developed by Lowe (2004). In his framework, the local maxima or minima of the Difference of Gaussians (DoG) were first used to locate potential key points. Then, some of the potential key-points were removed, if they had low contrast values or were poorly localized along the edges. In the remaining key-points, their dominant orientations were assigned. When the key-points were located and assigned with dominant orientations, the feature vectors were calculated at the key-points as the feature descriptions to make the key-points highly distinctive. The SIFT key-point detector and descriptor were expected to be invariant to scale and rotation.

Also, they could be robust to illumination changes. Therefore, they have been widely used for object recognition (Sirmacek and Unsalan, 2009), robust localization and mapping in a stereo system (Se et al. 2001), panorama stitching (Brown and Lowe, 2007), etc.

2.5 Speeded-up Robust Features (SURF)

SURF was presented by Bay et al. (2008). They adopted the concept of the Hessian matrix and approximated the determinant of the Hessian matrix with two box filters (Bay et al. 2008). The size of the box filters was up-scaled. Based on the response values of an image to these two filters, the SURF key-points in the image could be located. The descriptions could be further produced as the vectors based on the distribution of the intensity content within the local image regions of the points. The SURF detector and descriptor could utilize the integral images to reduce the computation time, which makes them almost three times faster than the SIFT detector and descriptor (Bay et al. 2008). Also, similar to the SIFT detector and descriptor, they are supposed to be robust against image rotation and scale (i.e. rotation and scale invariance).

2.6 Oriented FAST and Rotated BRIEFF (ORB)

ORB is the combination of the FAST point detector (Rostern et al. 2010) and the BRIEFF descriptor (Calonder et al. 2010) with several improvements. First, Harris corner measures were calculated and used to remove potential edge points. Only those corner points with high confidence values were kept. Then, the orientation of each corner point was estimated based on the intensity centroid of the local image patch around the corner (Rublee et al. 2011). The orientation information could help to identify the corresponding BRIEFF test pattern, which made the ORB description rotation-invariant. In addition to the rotation-invariance, another benefit of using the ORB detector and descriptor is their computational efficiency. This is especially true when they are compared with the SIFT and SURF feature detectors and descriptors (Rublee et al. 2011).

3. OBJECTIVE AND SCOPE

Although several visual feature detectors and descriptors have been developed, so far, none of them is perfect. Their performances vary significantly. That is why the appropriate selection is necessary for specific computer vision applications. For example, Senst et al. (2007) compared different visual feature detectors and indicated that the FAST detector was one of the efficient feature detectors for local optical flow tracking. Chandrasekhar et al. (2010) found that the SIFT descriptor had the better performance for mobile visual search than others.

The focus of this paper has been placed on investigating the effectiveness of different combinations of visual feature detectors and descriptors in the RGB-D mapping process for retrieving and modeling as-built conditions in the building indoor environments. In order to select the appropriate combination of visual feature detectors and descriptors, this paper first implements a general framework for the RGB-D mapping. Then, the different combinations of the visual feature detectors and descriptors have been tested. Their RGB-D mapping accuracy and speed are compared. The visual feature detectors that are considered in the paper include the FAST, GFTT, SIFT, SURF, BRISK, and ORB, while the visual feature descriptors include the BRISK, SIFT, SURF, and ORB. All of these detectors and descriptors are common, and have been widely used in different computer vision applications.

4. FRAMEWORK FOR RGB-D MAPPING

A typical RGB-D mapping process includes the detection, description, and matching of visual features. Specifically, the visual features are first detected in the RGB images. These features are then distinctively described. Based on the feature descriptions, the common features in the consecutive RGB images are matched. The 2D matching results could be further extended into 3D. When the pairs of 3D matching points in consecutive point clouds are determined, the point clouds representing the building indoor environments from different RGB-D images could be merged and aligned. The overall RGB-D mapping process has been illustrated in Fig. 1.

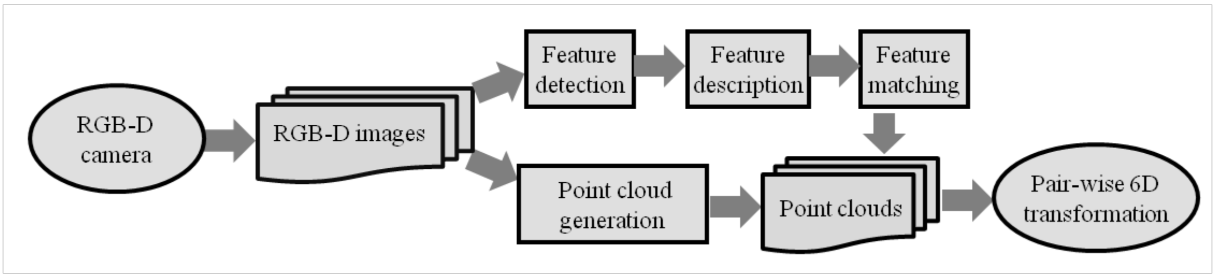


Fig. 1: Framework of RGB-D mapping.

5. EVALUATION CRITERIA AND EXPERIMENTS

The RGB-D mapping process mentioned above has been implemented and tested with different combinations of the visual feature detectors and descriptors. During the tests, the mapping accuracy and speed, as two main evaluation criteria, are recorded to measure the effectiveness and efficiency of different combinations of visual feature detectors and descriptors. Here, the mapping accuracy is determined by calculating the difference between the camera positions estimated from the mapping process (i.e. estimated trajectory) and the real positions of the camera (i.e. ground truth). The mapping speed is determined by the duration taken when performing the RGB-D mapping with each combination of the visual feature detectors and descriptors.

The specific configuration of the platform used to evaluate the RGB-D mapping process has been listed in Table 1. A total of seven RGB-D datasets have been used for the evaluation purpose. The datasets include freiburg1_xyz, freiburg1_rpy, freiburg1_360, freiburg1_desk, freiburg1_desk2, freiburg1_floor, and freiburg1_room. All were prepared by Strum et al. (2012) in the Computer Vision Groups at the Technische Universität München, each of which contains the RGB-D images plus the camera positions recorded (Strum et al. 2012). The real positions of the camera were captured by a motion capture system and they were included in the datasets to construct the ground-truth trajectories for the determination of the mapping accuracy.

Table 1: Configuration of the platform for the evaluation of the framework

Software	Operating System	Ubuntu 12.0.4 LTS
	C++ Code Compiler	gcc 4.6
Hardware	Central Processing Unit (CPU):	Intel(R) Core (TM) i7-2600K CPU @ 3.4 GHz
	Graphic Processing Unit (GPU):	NVIDIA GeForce GTX 560 Ti (1280 megabytes)
	Memory:	16 gigabytes (4x4 gigabytes)
	Motherboard	ASUS P8Z68-VPRO (Intel Z68 Chipset)
	Hard drive	Toshiba MK5061GSYN
	Operating System	Ubuntu 12.0.4 LTS (32 bits)

Different combinations of the visual feature detectors and descriptors have been implemented and tested in the RGB-D mapping process. The combinations (i.e. detector/descriptor) include BRISK/BRISK, BRISK/SIFT, BRISK/SURF, FAST/BRISK, FAST/SIFT, FAST/SURF, GHTT/BRISK, GHTT/SIFT, GHTT/SURF, ORB/BRISK, ORB/ORB,, ORB/SIFT, ORB/SURF, SIFT/BRISK, SIFT/SIFT, SIFT/SURF, SURF/BRISK, SURF/SIFT, and SURF/SURF. The implementations of these visual feature detectiors and descriptors could be found in the Open Source Computer Vision (OpenCV) library (Bradski and Kaehler, 2008). The GPU support has not been considered when implementing these feature detectors and descriptors.

Fig. 2 illustrates the results of using the combination of the SURF/SURF for the RGB-D mapping, when the dataset, freiburg1_xyz, was used for the evaluation. In the figure, it could be seen that the point clouds newly generated were progressively added into existing ones, and the number of the 3D poings kept growing. Meanwhile, the camera positions during the RGB-D mapping process could be estimated and recorded correspondingly.

Table 2 and Table 3 summarized the results for the seven datasets that have been tested so far. According to the test results, it could be found that the combination of the SURF/BRISK produced the most accurate RGB-D mapping results followed by the combination of the SURF/SIFT. However, the use of the SIFT descriptor may significantly increase the RGB-D mapping duratoin. Therefore, it is recommended to use the support of the GPU, if the SIFT descriptor has to be selected. The combination of the SIFT/SURF produced the most inaccurate RGB-D mapping results, compared with other possible combinations, and it is highly not recommended. As for the runnting time required, the combination of the ORB/ORB is taster than the other combinations. In contrast, the use of the SIFT/SIFT is the slowest.

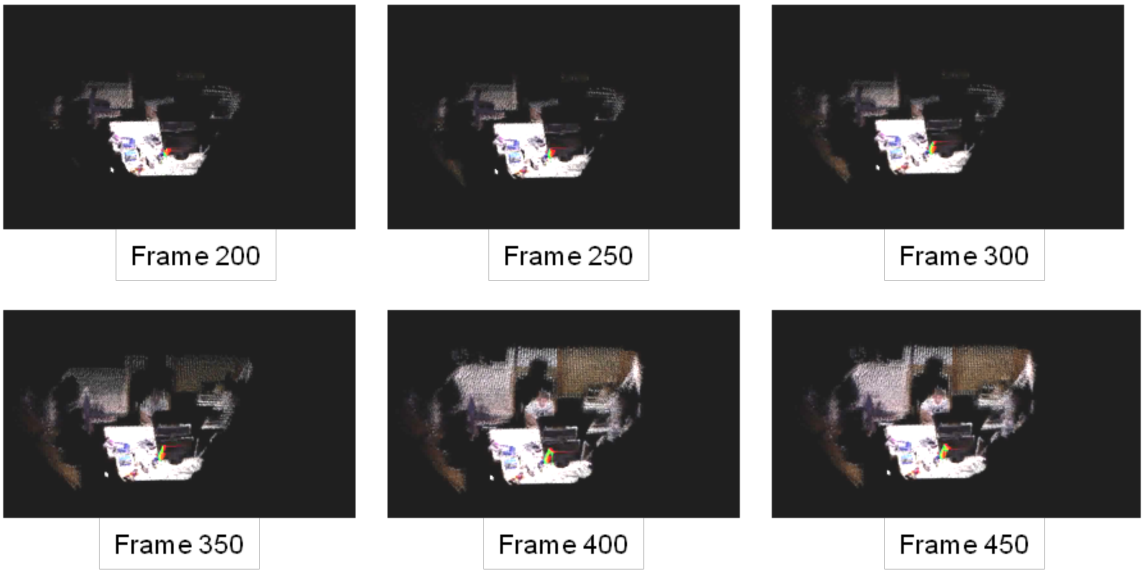


Fig. 2: RGB-D mapping results for the dataset freiburg1_xyz.

Table 2: Average error for different detector/descriptor combinations

		Detectors					
		BRISK	FAST	GFTT	SIFT	SURF	ORB
Descriptors	BRISK	0.2244	0.2690	0.1931	N/A	0.1873	0.2480
	SIFT	0.2079	0.2132	0.2272	0.3182	0.1891	0.2815
	SURF	0.1965	0.2394	0.2451	0.5420	0.2105	0.2374
	ORB	N/A	N/A	N/A	N/A	N/A	0.2402

Table 3: Running time (second) for different detector/descriptor combinations

		Detectors					
		BRISK	FAST	GFTT	SIFT	SURF	ORB
Descriptors	BRISK	10.7938	3.9642	5.3018	N/A	11.0563	2.6676
	SIFT	20.0081	3.9901	5.7614	48.7552	19.9264	8.5529
	SURF	10.6324	3.9859	5.0941	39.3383	11.0458	2.5961
	ORB	N/A	N/A	N/A	N/A	N/A	1.7230

In order to show the practicality of the proposed RGB-D mapping framework and the likelihood of uptake by the construction industry, the author used the framework for the generation of 3D point cloud of an office in the EV building at Concordia University. Considering one scan could not capture the full scene of the office, 3D points from each scan are progressively registered (Fig. 3). The 3D points generated from the proposed framework record the building geometry and actual details of building elements, which is useful to facilitate multiple building assessment and management tasks, such as construction errors identification and on-site communication and coordination between different parties.

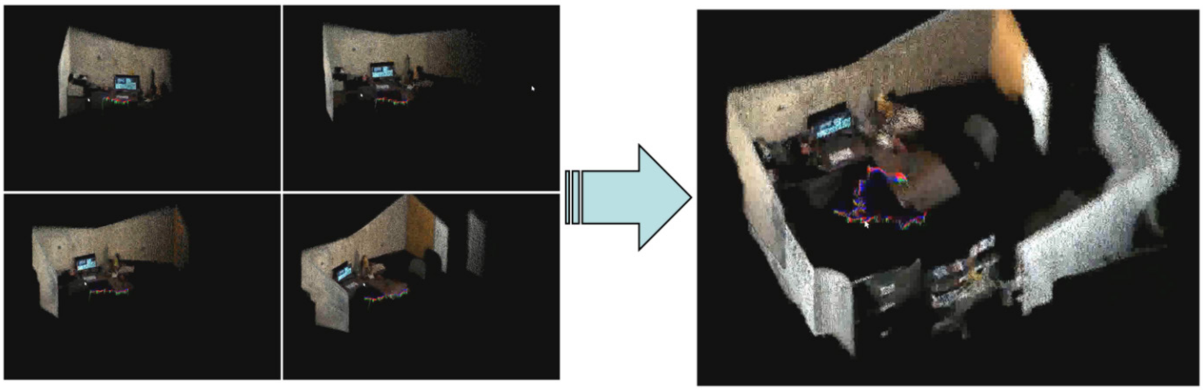


Fig. 3: 3D point clouds registration

6. CONCLUSIONS AND FUTURE WORK

3D as-built information of building elements have been identified useful, when addressing the problems related to building assessment and management. However, the current process for retrieving and modeling such information is labor intensive and time consuming. In order to address this issue, several research studies have been proposed, and the rececent work using the the RGB-D cameras is promising. The RGB-D camera is portable and convenient to use. Also, it could capture the RGB-D images and generate the 3D point clouds with the RGB-D mapping almost in real time. All of these benefits make the cammera become a good choice for the retrieval and modeling of as-built information of building elements especially in the indoor environments.

This paper investigated the effectiveness of different combinations of common visual feature detectors and descriptors on the RGB-D mapping process, considering the RGB-D mapping plays an imortant role in the retrieval and modeling of as-built information. Several common visual feature detectors (BRISK, FAST, GFTT, SIFT, SURF, and ORB) and descriptors (BRISK, SIFT, SURF, and ORB) have been selected and their different combinations have been evaluated. The main evaluation criteria include the mapping ccuracy and speed. A total of seven RGB-D datasets have been used for the evaluaiton purpose. The evaluation results from these datasets indicated that the combination of the SURF/BRISK could reach more accurate RGB-D mapping results than other possible combinations. Also, the combination of the ORB/ORB could produce the fastest registration speed, if there is no GPU support for all the combinations.

7. ACKNOWLEDGEMENT

This paper is based in part upon the work supported by the National Science and Engineering Research Council (NSERC) of Canada. Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the author(s) and do not necessarily reflect the views of the NSERC.

8. REFERENCES

Adan, A., Xiong, X., Akinci, B., and Huber, D. (2011). "Automatic creation of semantically rich 3D building models from laser scanner data," Proc. of ISARC 2011, Seoul, Korea

Bay, H., Tuytelaars, T., and Van Gool, L., (2008), "SURF: Speeded Up Robust Features.", Computer Vision and Image Understanding (CVIU), 110(3): 346--359.

Bradski, G. and Kaehler, A. (2008). " Learning OpenCV - Computer Vision with the OpenCV Library." O'Reilly Media Publisher, Oct. 1, 2008, ISBN-10: 0596516134

Brown, M. and Lowe, D. (2007). "Automatic panoramic image stitching using invariant features," International Journal of Computer Vision, 74(1): 59-73.

Calonder, M., Lepetit, V., Strecha, C. and Fua, P. (2010). “BRIEF: binary robust independent elementary features”, In: European Conference on Computer Vision, pp. 778-792. Heraklion, Crete, Greece, Sept. 5-11, 2010

Chandrasekhar, V., Chen, D., Lin, A., Takacs, G., Tsail, S., Cheung, N-M., Reznik, Y., Grzesczuk, R., and Girod, B., (2010). "Comparison of local feature descriptors for mobile visual research." In: International Conference on Image Processing, pp. 3885-3888. Hongkong, Sept. 36-29, 2010.

Engelhard, N., Endres, F., Hess, J., Sturm, J., and Burgard, W. (2011), " Real-time 3D visual SLAM with a hand-held camera." In Proc. of the RGB-D Workshop on 3D Perception in Robotics at the European Robotics Forum, 2011.

Harris, C. and Stephens, M. (1988). "A combined corner and edge detector". In: Proc. of the 4th Alvey Vision Conference. pp. 147–151.

Henry, P., Krainin, M., Herbst, E., Ren, X., Fox, D., (2010). "RGB-D Mapping: Using Depth Cameras for Dense 3D Modeling of Indoor Environments", In: Proc. of International Symposium on Experimental Robotics, Delhi, India.

Klein, G., and Murray, D. (2007). "Parallel Tracking and Mapping for Small AR Workspaces. In: Proc. of 6th IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR’07). Nara, Japan, 2007.

Leutenegger, S., Chli, M. and Siegwart, R. (2011). " BRISK: Binary Robust invariant scalable keypoints." In: IEEE International Conference on Computer Vision (ICCV), pp. 2548-2555, Barcelona, Nov. 6-13, 2011

Lowe, D., (2004). “Distinctive Image Features from Scale-Invariant Keypoints”, International Journal of Computer Vision, 60, 2, pp. 91-110, 2004.

Pettee, S (2005). "As-builts - problems and proposed solutions." CM eJournal, First Quarter: 1-19. <http://cmaanet.org/files/as-built.pdf> (June 10, 2012)

Rosten, E. and Drummond, T. (2006). "Machine learning for high-speed corner detection." In: European Conference on Computer Vision, Vol. 1, pp. 430–443. May, 2006.

Rosten, E., Porter, R., Drummond, T. (2010). " Faster and better: a machine learning approach to Corner Detection." IEEE Trans. PAMI 32(1): 105-119.

Se, S., Lowe, D., Little, J. (2005). "Vision-based global localization and mapping for mobile robots", IEEE Transactions on Robotics 21(3): 364-375.

Senst, T., Unger, B., Keller, I., and Sikora, T. (2012). " Performance evaluation of feature detection for optical flow tracking." In: International Conference on Pattern Recognition Applications and Methods, Vol. 2, pp. 303-309., Vilamoura, Portugal, Feb. 6-8, 2012

Shi, J. and Tomasi, C. (1994). "Good features to track.", In: Computer Vision and Pattern Recognition, pp. 593 - 600. Seattle, WA., Jun 21 - 23, 1994.

Sirmacek, B. and Unsalan, C. (2009). "Urban area and building detection using SIFT keypoints and graph theory" IEEE Transactions on Geoscience and Remote Sensing, 47(4): 1156-1167.

Sturm J., Engelhard, N., Endres, F., Burgard, W., and Cremers, D. (2012). "A Benchmark for the Evaluation of RGB-D SLAM Systems", In: Proc. of the International Conference on Intelligent Robot Systems (IROS), Oct. 2012.

Zhu, Z. (2012) "Automated As-built Modeling with Spatial and Visual Data Fusion." Proc. of 12th International Conference on Construction Applications of Virtual Reality 1-2 November, 2012, Taipei, Taiwan

PERFORMANCE STUDY ON NATURAL MARKER DETECTION FOR AUGMENTED REALITY SUPPORTED FACILITY MAINTENANCE

Christian Koch & Markus König
Computing in Engineering, Ruhr University Bochum, Germany

Matthias Neges & Michael Abramovici
IT in Mechanical Engineering, Ruhr University Bochum, Germany

ABSTRACT: *The operation and maintenance phase is the longest and most expensive life-cycle period of building facilities. Operators need to perform activities to provide a comfortable living and working environment and to upkeep equipment to prevent functionality failures. For that purpose they manually browse, sort and select dispersed and unformatted facility information before actually going on the site. Although some software tools have been introduced they still spent 50% of the on-site work on inspection target localization and navigation.*

To improve these manual, time consuming and tedious procedures, the authors previously presented a framework that uses BIM-based Augmented Reality (AR) to support facility maintenance tasks. The proposed workflow contains AR supported activities, namely AR-based indoor navigation and AR-based maintenance instructions. An inherent problem of AR is marker definition and detection. As introduced, indoor natural markers such as exit signs, fire extinguisher location signs, and appliances' labels were identified to be suitable for both navigation and maintenance instructions. However, small markers, changing lighting conditions, low detection frame rates and accuracies might prevent the proposed approach from being practical.

In this paper the performance of natural marker detection will be evaluated under different configurations, varying marker types, marker sizes, camera resolutions, and lighting conditions. The detection performance will be measured using a pre-defined metric incorporating detection accuracy, tracking quality, frame rates, and robustness. The result will be a set of recommendations on what configurations are most suitable and practical within the given framework.

KEYWORDS: *Augmented Reality, Facility Maintenance, Natural Markers, Building Information Modeling, Detection Performance*

1. INTRODUCTION

The longest period in the lifecycle of a building is the operation and maintenance (O&M or FM) phase. In this phase facility managers and operators perform activities to provide a comfortable living and working environment as well as to upkeep equipment to prevent functional failures. Since over 85% of the entire lifecycle costs are spent on facility management (Teicholz 2004), improvements to the maintenance procedure will significantly reduce the overall building lifecycle budget.

Today's maintenance practice is characterized by dispersed and unformatted facility information that operators often need to manually browse, sort and select. Although software systems have recently been introduced, 50% of the on-site maintenance time is spent on localizing inspection targets and navigating to it inside a facility (Lee and Akin, 2011). Moreover, linked maintenance instructions are often multi-page documents, which sometimes are difficult to comprehend, in particular, in case of emergencies.

Although some recent research studies propose to use Building Information Models (BIM) by either integrating or linking work order information to them, not all necessary information needed is currently available in a digitally integrated and standardized model. Moreover, available UWB, WLAN, RFID and GPS indoor navigation approaches are validated, but they rely on costly equipment infrastructure for senders and readers. Existing Augmented Reality (AR) based solution use artificial markers for both navigation and maintenance instruction

Citation: Koch, C., König, M., Neges, M. & Abramovici, M. (2013). Performance study on natural marker detection for augmented reality supported facility maintenance. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

support. This kind of markers is tedious to be installed all over a facility and also comes along with esthetical issues.

Previously, the authors have introduced and tested a framework that can digitally support facility maintenance operators in performing their daily on-site maintenance jobs combining Building Information Models and natural markers for AR-based support (Koch et al. 2012). The proposed workflow is comprised of three major activities: (1) Digital Work Order Compilation (collecting relevant information), (2) AR-based Indoor Navigation (positioning and navigation), and (3) AR-based Maintenance Instructions (performing maintenance task).

The main contribution of this paper is to conduct and evaluate the performance of natural marker detection within the given framework. For this purpose, we test different configurations in a controlled environment varying marker types, marker sizes, camera resolutions, and lighting conditions. Based on pre-defined metrics incorporating detection accuracy, distances, frame rates, angles, and robustness the detection performance is measured. Finally, a set of recommendations on most appropriate and practical configurations within the given framework is given.

2. BACKGROUND

2.1 Current practices

In today's maintenance and repair practice facility operators need to gather and access dispersed and unformatted facility information in order to handle work orders (Akcamete et al. 2011). Typically, this information is handed over from the building design and the construction phase and is available in form of 2D drawings, spreadsheets, bar charts, field reports and paper-based guidelines. Collected in so-called Facility Document Repositories, the facility handover data is physically space consuming and might occupy an entire room (East et al. 2013). Recently, Computer-Aided Facility Management (CAFM) Systems for space management and Computerized Maintenance Management Systems (CMMS) for work order management have been introduced to digitally support operators in integrating preventive maintenance schedules and intervals, shop and installation drawings, cost control and documentation, device specifications and manuals, warranty information, replacement parts providers, as-is performance data, etc. (East et al. 2013, Akcamete et al. 2011).

However, in order to prepare an actual on-site maintenance job, operators need to identify the location of the maintenance item inside the building, the route towards it as well as relevant maintenance instruction manuals. According to Lee and Akin (2011), 50% of the on-site maintenance time is solely spent on localizing and navigating. Furthermore, linked maintenance instructions are often multi-page documents, which sometimes are difficult to comprehend, in particular, in case of emergencies.

2.2 Current research efforts

2.2.1 Indoor positioning and navigation

In addition to the location of the maintenance item (available in the BIM), it is necessary to know the operator's position inside the facility in order to support real-time indoor navigation. There is a vast amount of ongoing research in this area. As one example from the construction community, Khoury and Kamat (2009a) have evalutated three different wireless indoor position tracking technologies, in particular, Wireless Local Area Networks (WLAN), Ultra-Wide Band (UWB) and Indoor GPS positioning system. Indoor GPS has been identified as being superior, since it could estimate a mobile user's location with relatively low uncertainty of 1 to 2 cm. The main disadvantage of these technologies is the need for extra equipment installation and maintenance (both tags and readers), which involves a considerable cost factor.

Besides the position, the operator's view orientation needs to be determined to provide both location-aware and viewing direction-aware guidance. Here, sensors such as Inertial Measurement Unit (IMU), a combination of accelerometers and gyroscopes, and magnetic orientation sensors (e.g. a magnetic compass) are utilized. Khoury and Kamat (2009b) have used a solid-state magnetic field sensor, installed on the user's head, to track the user's dynamic viewpoint. This information has then been processed to identify building objects in the user's field to retrieve contextual information. Although, the user's position uncertainty is documented, the orientation accuracy has not been presented nor validated.

2.2.2 Performing maintenance task

Once the operator has reached the target, the third work order activity is the component maintenance. At this stage, he/she needs actual maintenance instructions and manuals. Lee and Akin (2011) have proposed to employ Augmented Reality to superimpose equipment-specific data, such as textual maintenance information and geometry, onto a live video stream (Fig. 1). This supports the fieldworker in better comprehending the on-site job. Even hidden parts of the equipment can be visualized in full scale. However, the main disadvantage is that fiduciary (artificial) markers have to be pre-installed on the component of interest, which is tedious and unesthetic, thus preventing this approach from being practically efficient.

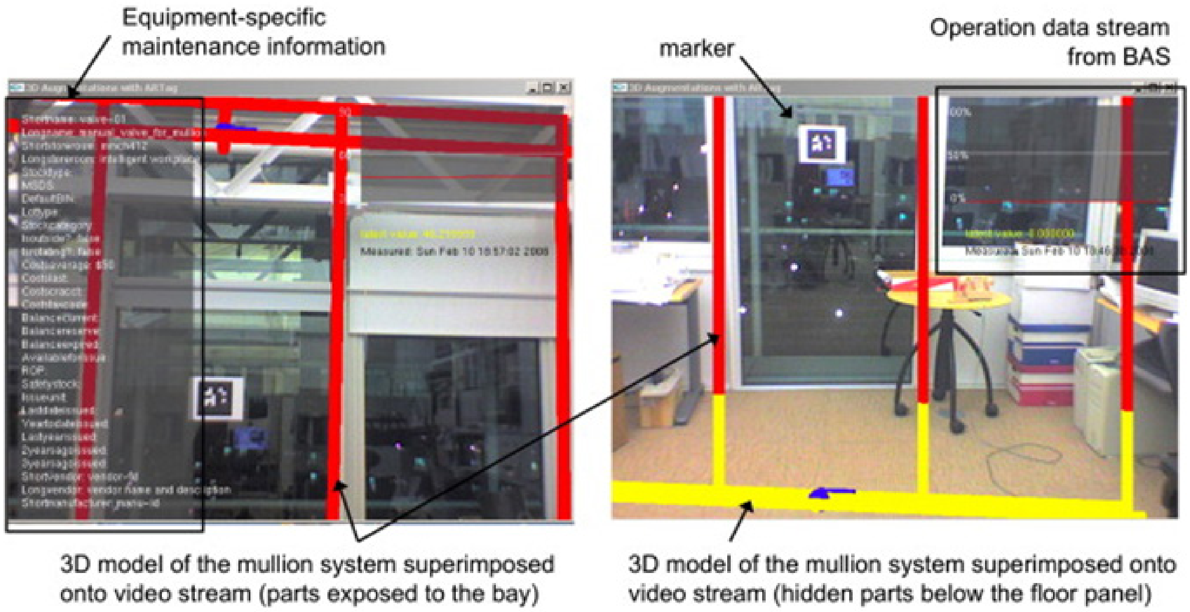


Fig. 1: AR-based computational fieldwork support for equipment operations and maintenance using artificial (ID) markers (Lee and Akins 2011).

In other industries, such as the mechanical engineering, Augmented Reality is used to support maintenance and repair tasks, for example on vehicle equipment such as engines (e.g. Henderson and Feiner 2011). Using a see-through Head Worn/Mounted Display (HWD/ HMD), the mechanic's natural view is augmented with text, labels, arrows, and even animated sequences designed to facilitate task comprehension, localization, and execution. However, the major disadvantages of HMDs are the low display resolution and the separate uncomfortable head-mounted device.

2.2.3 Previously proposed framework

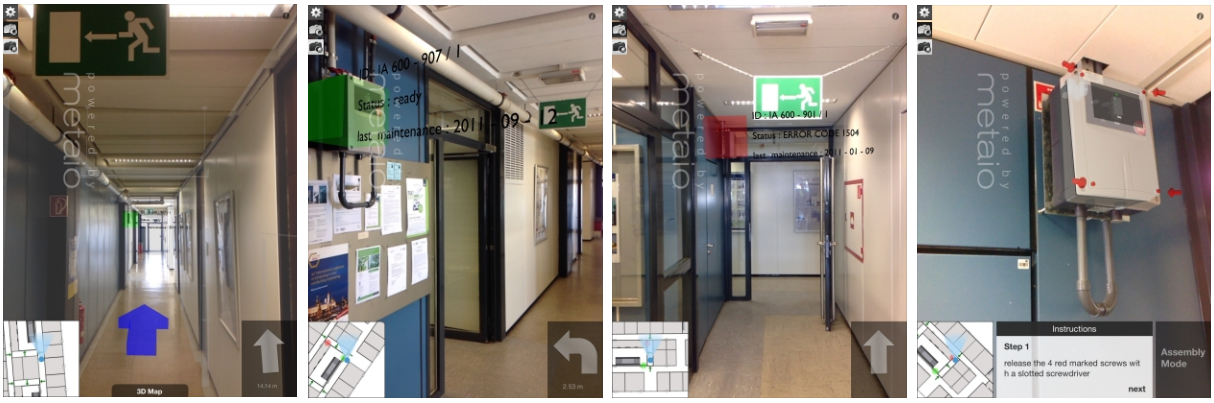
The authors previously presented a BIM-based Augmented Reality framework for facility maintenance using natural markers (Koch et al. 2012). The proposed framework comprises three major activities: digital work order compilation (collecting relevant BIM and FM information), AR-based indoor navigation (positioning and routing), and AR-based maintenance instructions (performing maintenance task). Within the latter two activities so-called natural markers, for example, exit signs, are employed as AR markers. AR markers are very distinctive images with known visual patterns and dimensions that are used as reference objects to superimpose virtual 3D content onto the camera's live view. In contrast to artificial markers, which are practically inefficient and unesthetic to install inside a building, natural markers have the advantage to be already available on-site. Koch et al. (2012) emphasized the potential of exit signs as they are very distinctive due to their color and shape, the have an appropriate size (not too small), and they are clearly visible since the have to be in case of emergencies. Moreover, Koch et al. (2012) implemented the framework on an iPad® 2 using the Augmented Reality framework metaio™ Mobile SDK 3.1 (Metaio 2013) and conducted several experiments in a controlled environment to highlight the potential of the proposed framework.

Promising experimental results of our previous work regarding an AR-supported indoor navigation to a defective smoke detector as well as AR-based smoke detector maintenance instructions are depicted in Fig. 2. A 3D model and 3D navigation arrows (Fig. 2a), 2D navigation arrows (Fig. 2a-c), 3D positions of intact and defective smoke detectors (Fig. 2b, c), animated 3D maintenance instructions (Fig. 2d), and the 2D user position on a map (Fig. 2a-d) are superimposed on the camera life view.

However, in order to validate the complete framework it is necessary to test the performance of the most essential framework part – the natural marker detection. While the previous work of the authors (Koch et al. 2012) introduced the overall framework and highlighted its potential, this paper presents the first specific experimental results on the actual performance of indoor natural marker detection.

2.3 AR markers for optical tracking

In AR applications, optical marker tracking is essential to determine the position and viewing direction of the camera. Based on the nature of the tracking algorithms, several types of markers can be distinguished.



(a) (b) (c) (d)

Fig. 2: Augmented life view: (a) superimposed 3D model, 3D navigation arrow and intact smoke detector position (green box), (b) showing left turn instruction and intact smoke detector (green color), (c) superimposed target smoke detector position (red box) and error code, (d) textual instructions (bottom) and superimposed 3D animated instructions (red arrows) (Koch et al. 2012).

- **ID Markers** are rectangular 2D markers used for simple AR applications. Since they have a fixed structure and distinctive black border they can be easily and very robustly detected and tracked (Fig. 3a). Using the inside pattern a few hundred markers with different encoded information can be configured.

- **Barcodes and Quick Response codes** are optical machine-readable 2D representations of data items. While barcodes are well-known (Fig. 4b), Quick Response (QR) code markers are similar to ID markers as they consist of black square modules arranged in a square grid on a white background (Fig. 3c). Based on that, they can be read by read by imaging devices and interpreted to extract information from the patterns.

- **Picture Markers** are somehow in between ID markers and Markerless. Similar to ID markers the have a strong and distinctive rectangular border. In contrast, however, they can contain any arbitrary image (containing enough visual content) inside the boundary (Fig. 3d). Due to their distinctive border they can be detected faster than borderless markers.

- **Markerless** is the (maybe misleading) term for 2D borderless markers that do not have an explicit rectangular boundary, but need to have moderately textured content. Based on distinctive visual features (e.g. point descriptors) and advanced algorithms they can be robustly detected and tracked (Fig 3e).

- **Markerless 3D** tracking is the most advance optical tracking method that facilitates the detection and tracking of any real world object. However, the 3D object needs to have enough visual features and needs to be scanned from several perspectives in order to determine its distinctive visual features (Fig 3f).

(a) (b) (c) (d) (e) (f)

Fig. 3: Different types of AR markers for optical tracking (Metaio 2013): (a) ID marker, (b) barcode marker, (c) QR code marker, (d) picture marker, (e) markerless (borderless) marker, and (f) markerless 3D tracking.

Regarding the proposed framework that suggests using natural markers, such as exit signs, the most appropriate marker type is the picture marker. This is due to the fact that, for example, exit signs as well as fire distinguisher signs have a rectangular shape, a strong boundary and a distinctive inner visual content.

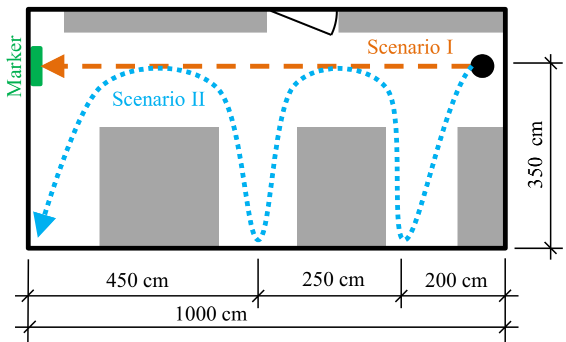
2.4 Problem statement and objectives

As previously proposed by the authors, indoor natural markers such as exit signs, fire extinguisher location signs, and appliances' labels have to potential to support AR-based navigation and maintenance instructions (Koch et al. 2012). However, small markers, changing lighting conditions, low detection frame rates and inaccuracies might prevent the proposed framework from being practical. Moreover, there is no study on the actual performance of indoor natural marker detection available. For these reasons, the objectives of this paper are to design, conduct and evaluate experiments to determine the detection performance of indoor natural markers and to give recommendations on what configurations are most practical within the given framework.

3. PERFORMANCE STUDY METHODOLOGY

3.1 Experimental setup

In order to conduct the performance test we set up a controlled environment in one of our laboratory (Fig. 4a). As depicted in Fig. 4 two different scenarios were designed. While in scenario I a straight walk towards the marker was performed (about 1500 frames per setting), in scenario II a curved path with viewing direction towards the marker was investigated (about 4000 frames per setting). Moreover, we varied the type of the marker (exit sign, fire extinguisher sign, text sign), the size of the marker image template (width of 50, 100, and 300 pixels), and the camera resolution (192x144, 480x360, and 640x480 pixels) (Fig. 4b). The three markers have a natural size of 400x200, 210x210, and 300x160 mm, respectively. In addition, for the exit sign marker we conducted test under artificial lighting condition by switching on the ceiling light in the lab. According to our previous study we implemented the AR test application on an iPad® 2 based on the Augmented Reality framework metaio™ Mobile SDK 4.1.2 using the Picture Marker Tracking functionality (Metaio 2013). To achieve representative results we ran the same test three times for each setting. Moreover, two people of different height and different walking behavior and speed conducted the tests.



(a)

Configurations

Marker type	Exit 	Fire 	Text Das Mitbringen von Tieren ist nicht zulässig.
Marker size	width 50 px	width 100 px	width 300 px
Camera resolution	192x144 px	480x360 px	640x480 px

(b)

Fig. 4: Experimental setup: (a) controlled environment in the lab, (b) experiment configurations.

3.2 Performance metrics

While running the test, the AR test application recorded performance data, such as the tracking quality, the frame rate, the distance to the marker as well as the horizontal angle to the marker. Based on these values we calculated the following performance metrics.

- **Detection rate:** The detection rate is calculated for every single configuration using the formula below. It is assumed that the number of frames with successful detection is equal to the number of frames with detected distances larger than zero.

detection rate = number of frames with successful detection / number all frames

- **Quality:** The current tracking quality is provided by the metaio SDK. It is a value between 0.5 and 1.0, with 0.5 as minimum quality to detect at all, and 1.0 with (assumed) perfect tracking.

quality = [0.5, 1.0]

- **Frame rate:** The current frame rate is determined by means of the metaio SDK and is calculated as number of processed frames per second.

- **Robustness:** It is assumed that the person walks smoothly and continuously along the designed path at almost the same speed without any jumps in speed and position. Under this assumption the tracking robustness is determined as the relative deviation of the provided consecutive distance and angle values. Thus, it can somehow be understood as detection precision.

4. EXPERIMENTAL RESULTS

4.1 Scenario I: Straight walk

4.1.1 Detection rate

Table 1 depicts the marker detection rates for the diverse settings in scenario I. It is clearly visible that the markers *exit sign* and *fire sign* outperform the marker *text sign*. This is most likely due to the very narrow border of the text sign marker. For this reason we excluded the text sign marker as well as the camera resolution of 192x144 from all subsequent test settings. Moreover, under natural lighting conditions the configuration settings 50-480x360, 50-640x480, 300_480x360, and 300-640x480 performed best. Note the detection rate improvement under artificial lighting condition for the marker exit sign.

Table 1: Detection rate [%] for scenario I (straight walk) depending on marker type, marker size and camera resolution. Note the values for artificial lighting in case of the exit sign marker.

Marker size (width) [px]	**50**	**50**	**50**	**100**	**100**	**100**	**300**	**300**	**300**
Exit sign / Art. light	67.0/63.4	98.9/96.8	98.8/98.8	63.4/61.6	89.3/97.5	88.6/98.6	42.5/59.8	95.6/96.8	93.6/98.3
Fire ext. sign	42.3	95.4	98.4	47.3	96.9	96.9	44.1	97.0	97.0
Text sign	26.8	53.7	54.6	27.7	58.6	67.4	36.7	58.2	70.4
Camera resolution [px]	**192x144**	**480x360**	**640x480**	**192x144**	**480x360**	**640x480**	**192x144**	**480x360**	**640x480**

4.1.2 Tracking quality

Fig. 5 (top) highlights the achieved tracking qualities for the marker *exit sign* and the marker *fire sign*, respectively, plotted with regard to the marker distance depending on the marker size and the camera resolution (e.g 50/630 means: marker size 50px and camera resolution). In case of the exit sign marker the settings 50/480 and 300/640 outperform the other settings. However, in case of the fire sign marker the settings 50/480, 100/640 and 100/480 are best. These findings are both valid for the tracking quality and the achieved maximum marker distance.

4.1.3 Tracking frame rate

In analogy to the quality, Fig. 5 (bottom) highlights the achieved tracking frame rates (only for successful detection) for the marker *exit sign* and the marker *fire sign*, respectively, plotted with regard to the marker distance depending on the marker size and the camera resolution. In general it was found that the camera resolution has a much larger impact on the achieved frame rate than the marker size. Moreover, the frame rate increases while the marker distance decreases. However, all tested settings achieved a suitable average frame rate of 25 to 30 fps.

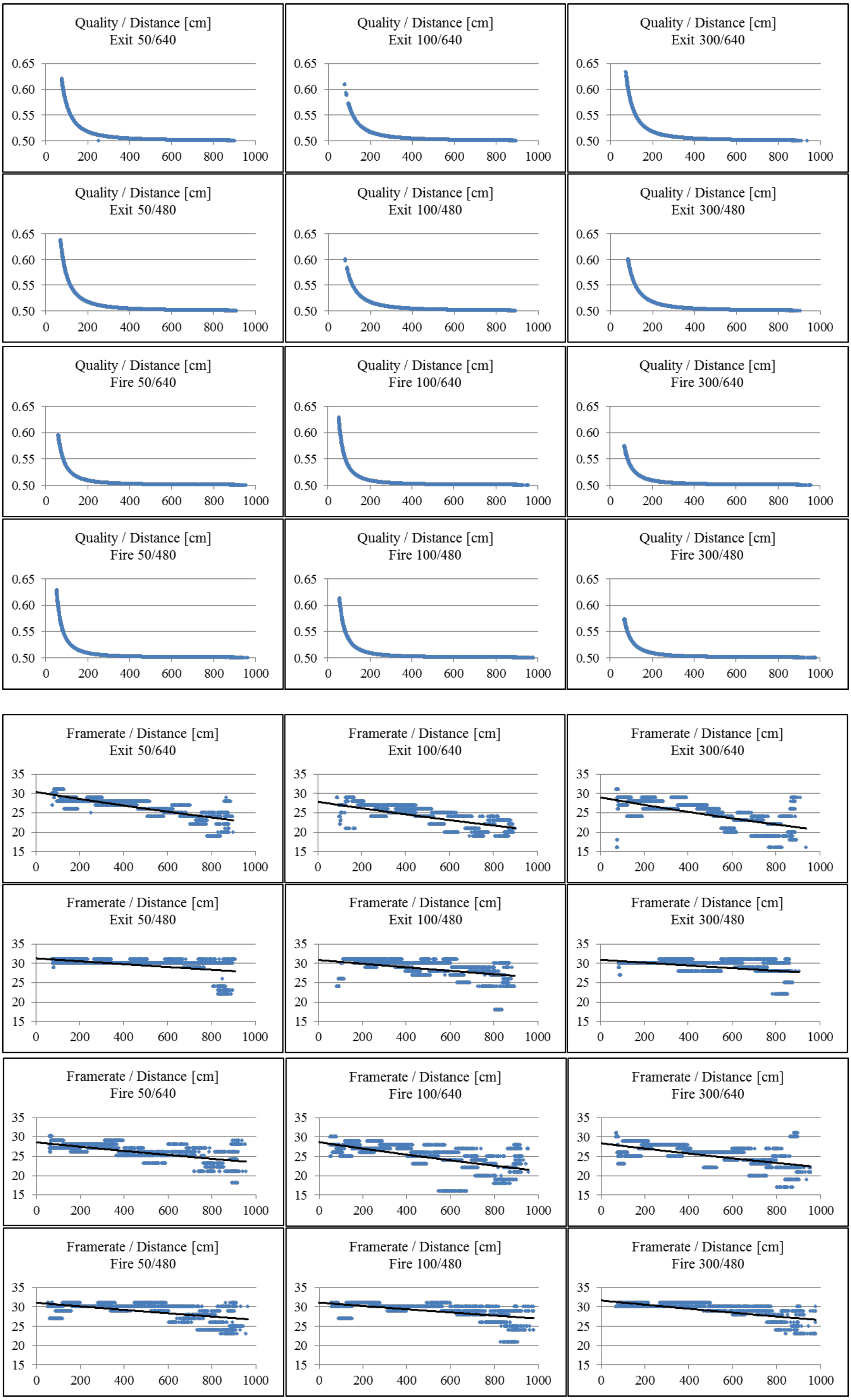


Fig. 5: Tracking quality (top) and tracking frame rate (bottom) for scenario I depending on marker distance.

4.1.4 Tracking robustness

In Fig. 6, the robustness of the marker tracking is depicted, both in terms of distance deviation and horizontal angle deviation plotted with regard to the marker distance. It is clearly visible that the exit sign marker outperforms the fire sign marker as the value corridors are much narrower. Moreover, the maximum distance errors and the angle errors for exit sign marker are much smaller than the corresponding ones for the fire sign marker. However, the maximum errors are justifiable as they are about 50 cm in distance and 20 degrees for the angle.

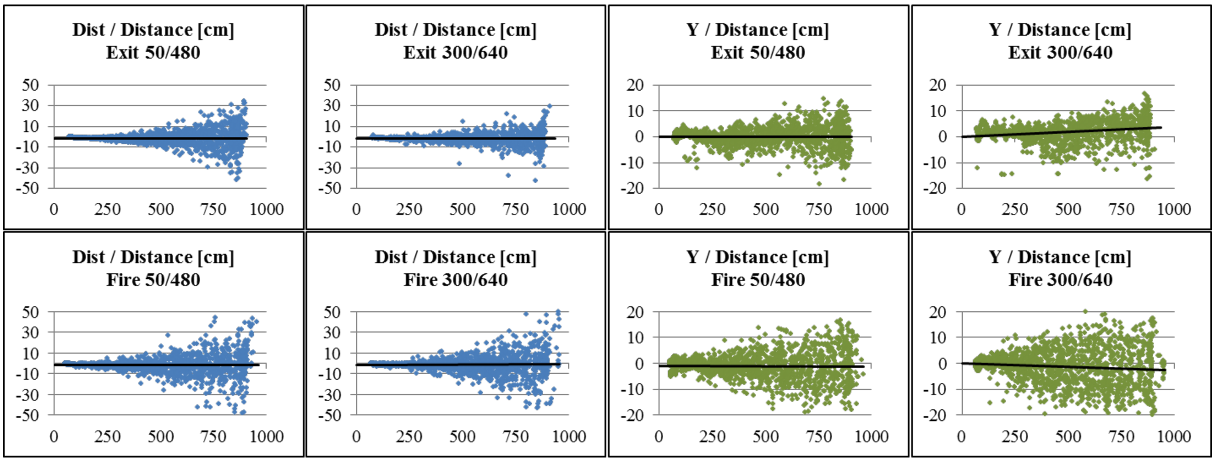


Fig. 6: Tracking robustness for scenario I depending on marker type, marker size and camera resolution.

4.1.5 Lighting condition

Fig. 7 highlights the result that both tracking quality and robustness benefit from artificial ceiling lighting. This is concluded because the tracking quality increases in average from below 0.65 to above 0.65, and robustness corridor for both the distance and angle deviation is much narrower in case of artificial lighting. In addition note the detection rate improvement depicted in Table 1.

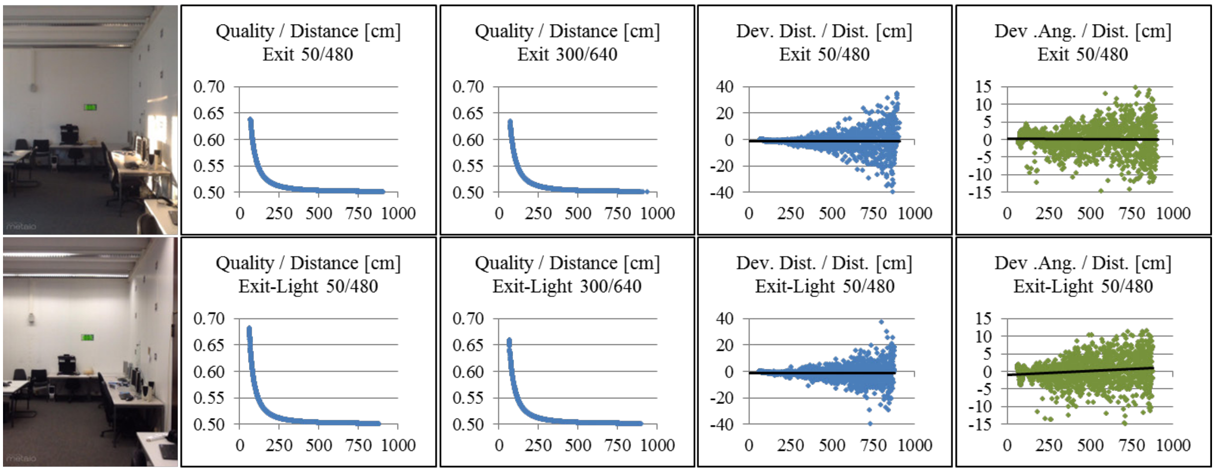


Fig. 7: Influence of lighting condition on tracking quality and robustness for scenario I and exit sign marker.

4.2 Scenario II: Curved walk

4.2.1 Detection rate

In analogy to scenario I, Table 2 summarizes the detection rates for scenario II. Note that the settings 50-480x360, 50-640x480, 300-480x360 and 300-640x480 outperform the other settings.

Table 2: Detection rate [%] for scenario II (curved walk) depending on marker type, marker size and camera resolution.

Marker size (width) [px]	**50**	**50**	**50**	**100**	**100**	**100**	**300**	**300**	**300**
Exit sign	64.14	92.43	95.36	66.99	77.41	77.96	61.39	94.83	93.58
Fire ext. sign	21.65	86.95	89.59	23.70	85.27	89.93	33.04	85.63	90.59
Camera resolution [px]	**192x144**	**480x360**	**640x480**	**192x144**	**480x360**	**640x480**	**192x144**	**480x360**	**640x480**

4.2.2 Tracking quality

Fig. 8 depicts the achieved tracking quality plotted with regard to the detected horizontal angle. Here, the exit sign marker outperforms the fire sign marker. Moreover, the settings 50-480x360 and 300-480x360 seem to be best.

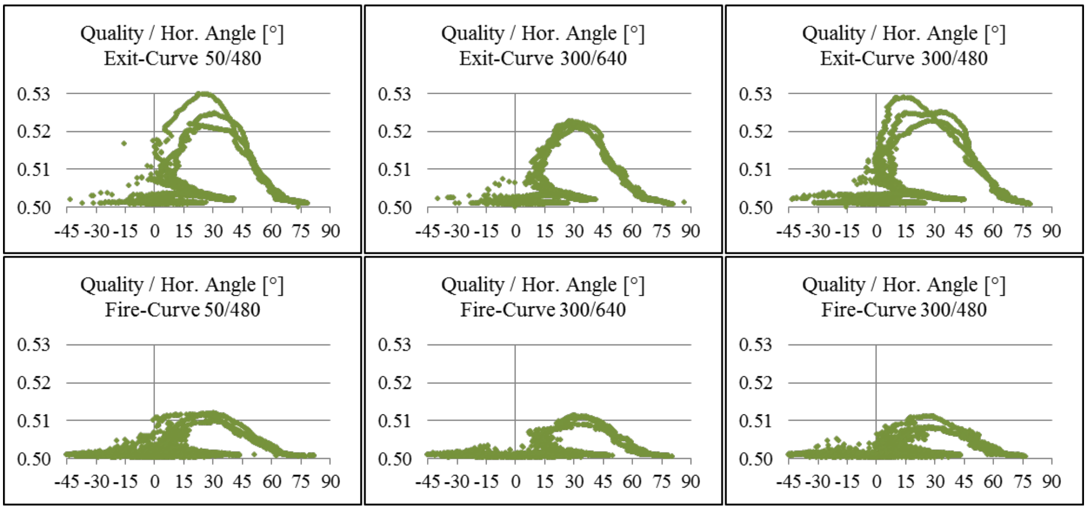


Fig. 8: Tracking quality for scenario II depending on marker type, marker size and camera resolution.

4.2.3 Tracking robustness

Fig. 9 highlights the tracking robustness in terms of the detected horizontal angle plotted with regard to the frame number. Again, the exit sign marker outperforms the fire sign marker as it achieves a less amount of negative, thus wrong angle estimations. However, note the achieved detected angle is almost 85 degrees.

5. CONCLUSION

The longest phase in a facility's lifecycle is its operation and maintenance period, during which facility operators perform activities to provide a comfortable living and working environment as well as to upkeep equipment to prevent functional failures. In current practice operators need to manually process dispersed and unformatted facility information, which takes 50% of the on-site maintenance time for localizing and navigating.

Based on a previously presented framework that suggest to support on-site facility maintenance activities using BIM based Augmented Reality, this paper has highlighted the results of a performance study of natural marker detection. The performance has been evaluated under different configurations, varying marker types, marker sizes, camera resolutions, and lighting conditions. Several metrics, namely detection rate, tracking quality, frame rates, and robustness have been defined to actually measure the detection performance.

To conclude, the presented performance study reveals the high potential of natural markers for AR-based FM support as the detection rate can achieve more than 95%, the marker distance can be about 10 meters, the marker can be detected up to an angle of 85 degrees, and the maximum distance deviations and angle deviations are less than 50 cm and 20°, respectively.

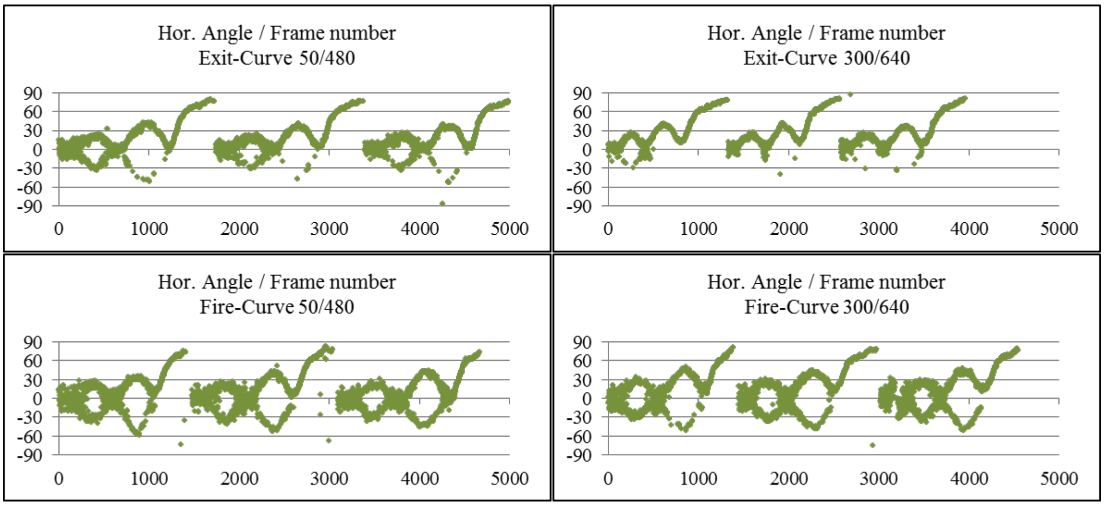


Fig. 9: Tracking robustness for scenario II depending on marker type, marker size and camera resolution.

Based on the presented results, it is finally recommended

- to use natural markers that have a strong, distinctive border with high contrast to the background,
- to have artificial lighting switched on
- to use settings, such as 50-480x360 or 300x640, depending on the desired tracking quality and frame rate

6. REFERENCES

Akcamete, A., Liu, X., Akinci, B., Garrett, J.H. (2011). Integrating and Visualizing Maintenance and Repair Work Orders in BIM: Lessons Learned from a Prototype. In: *11th International Conference on Construction Applications of Virtual Reality*, 2011, Weimar, Germany.

Ayer, S.K., Messner, J.I., Anumba, C.J. (2011). Determining the appropriate role for mixed reality technologies in facility management. In: *11th International Conference on Construction Applications of Virtual Reality,* 2011, Weimar, Germany.

East, E.W., Nisbet, N., Liebich, T. (2013). The Facility Management Handover Model View. *Journal of Computing in Civil Engineering* 27(1) 61–67.

Ergen, E., Akinci, B., East, B., Kirby, J. (2007). Tracking Components and Maintenance History within a Facility Utilizing Radio Frequency Identification Technology. *Journal of Computing in Civil Engineering* 22(1) 11–20.

Henderson, S., Feiner, S. (2011). Exploring the Benefits of Augmented Reality Documentation for Maintenance and Repair. *IEEE Transactions on Visualization and Computer Graphics* 17(10) 1355–1368.

Khoury, H.M., Kamat, V.R. (2009a). Evaluation of Position Tracking Technologies for User Localization in Indoor Construction Environments. *Automation in Construction* 18(4) 444–457.

Khoury, H.M., Kamat, V.R. (2009b) High-precision Identification of Contextual Information in Location-aware Engineering Applications. *Advanced Engineering Informatics* 23(4) 483–496.

Ko, C. (2009). RFID-based Building Maintenance System. *Automation in Construction* 18(3) 275–284

Koch, C., Neges, M., König, M., Abramovici, M. (2012). BIM-based Augmented Reality for Facility Maintenance using Natural Markers. In: *Proceedings of the 19th International EG-ICE Workshop*. 2012, Herrsching, Germany.

Lee, S., Akin, Ö. (2011). Augmented reality-based computational fieldwork support for equipment operations and maintenance. *Automation in Construction* 20(4) 338-352.

Metaio (2013). Metaio Mobile SDK. http://www.metaio.com/software/mobile-sdk/ (May 2013)

Motamedi, A., Saini, R. Hammad, A., Zhu, B. (2011). Role-based Access to Facility Lifecycle Information on RFID Tags. *Advanced Engineering Informatics* 25(3) 559–568.

Teichholz, E. (2004). Bridging the AEC/FM Technology Gap, *IFMA Facility Management Journal*.

BIM FOR FACILITY MANAGEMENT: A REVIEW AND A CASE STUDY INVESTIGATING THE VALUE AND CHALLENGES

Graham Kelly, Michael Serginson & Steve Lockley
BIM Academy, Faculty of Engineering and Environment, Northumbria University, Newcastle, UK

Nashwan Dawood & Mohamad Kassem
Technology Futures Institute, Teesside University, Middlesbrough, UK

ABSTRACT: *For many years the issue of how to run buildings efficiently and effectively has posed a considerable challenge. This debate has had renewed significance since the emergence of Building Information Modelling (BIM) processes and the proposition that BIM information, captured during the facilities lifecycle, can help improve the efficiency of Facility Management (FM). Using this proposition as a starting point, the overarching aim of this paper is to investigate the value-adding potential of BIM and the challenges hindering its exploitation in FM. The literature review showed the BIM value adding potential stems from improvement to current manual processes of information handover. It also adds improvement to the accuracy of FM data and increases the efficiency of work orders execution, in terms of speed, to accessing data and locating interventions. It was also revealed that there is lack of real world case studies, especially in the case of existing buildings, despite new constructions representing a small percentage of the total building stock in a typical year. The case study was conducted on an existing asset composed of 32 non-residential buildings in Northumbria University's city campus. This was done to empirically investigate the value of BIM in a specific FM function (i.e. space management). The results provided evidence of the value of BIM in improving the efficiencies of FM work orders and the accuracy of geometric information records.*

KEYWORDS: *Building information modelling, facility management, computer-aided facility management,*

1. INTRODUCTION

The operational phase of a building is the main contributor to the building lifecycle cost. Estimates show that the lifecycle cost is five to seven times higher than the initial investment costs (Lee et al. 2012) and three times the construction cost (BIM Task Group 2013). There has been a tremendous economic and environmental need to manage both new and existing facilities in an efficient way. The industry has seen this debate renewed with the emergence of BIM, and the proposition that BIM data captured during the project lifecycle could improve the efficiencies of facility management functions. Facilities management (FM) is an umbrella term under which a wide range of property and user related functions are brought together for the benefit of the organization and its employees as a whole (Spedding and Holmes 1994). FM is holistic in nature, covering everything from real estate and financial management to maintenance and cleaning (Atkin and Brooks 2009). Governments around the world have recognised the inefficiencies affecting the construction industry in general, and have recommended and mandated the use of Building Information Modelling (BIM) as a strategy to addressing a declining productivity. Building Information Modelling (BIM) is the process of generating and managing information about a building during its entire lifecycle (BSI, 2010). For example, the UK Government has mandated BIM level 2 – Managed 3D environment held in separate discipline BIM models – on all public building projects from 2016, including the handover of digital data required for the operational phase (HM Government 2013) .

Tremendous research efforts have been devoted to address various aspects relating to the implementation of BIM in planning, design and construction processes. BIM for FM is an emerging area and there is still limited knowledge available on the subject. In addition, efforts investigating BIM applications in FM have mainly focused on new buildings despite new works making up only 1-2 % of the total building stock in a typical year. (Kincaid 2004). There are also lack of real world cases on BIM applications in FM (Becerik-Gerber et al. 2012). In this paper, a contribution to this gap is added by investigating the value and challenges of BIM in FM using an extensive literature review and a real world case study. The case study was conducted on 32 non-residential buildings in Northumbria University's city campus.

Citation: Kelly, G., Serginson, M., Lockley, S., Dawood, N. & Kassem M. (2013). BIM for facility management: a review and a case study investigating the value and challenges. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

2. CHALLENGES

There is an agreement about potential applications and benefits of BIM in FM, evidenced by the support of some pioneering FM organisations (Becerik-Gerber et al. 2012) and the vibrant research and development efforts addressing this area. The understanding of the challenges affecting BIM for FM applications is crucial at this stage.

One of the main challenges that is often discussed in workshops and reported in literature is the lack of processes in place for updating the designed model with as built information (Gu and London 2010). It is also unclear who is best placed to load data in and maintain the model (Becerik-Gerber et al. 2012). Facility managers have traditionally been included in the building lifecycle in a very limited way and at the late stage of facility handover to clients (Azhar 2011). Additionally, design decisions are not usually challenged for their impact on operational cost or maintenance (British Institute of Facilities Management 2012). As a result of these challenges, BIM data for FM is either lacking or inadequate. "*The FM field relies heavily on getting usable data from a BIM model to do anything meaningful with it. All too often, this data is not really there or is inaccurate, as the model has not been updated with any design changes made after the design phase and is therefore not an accurate model of the facility as it is built*" (Khemlani 2011). East proposes that facility maintenance contractors are paid to survey the existing building to capture as-built conditions and the owner should pay twice - once for the construction contractor to complete the documents at the end of construction - and again for the maintenance contractor survey (East and Brodt 2007).

The current FM industry cultural approach to adopting new processes and technologies is considered as a key challenge. The FM industry is quite rigid in its approach to new technology, and unless BIM for FM benefits are clearly proven, its uptake in the FM industry will continue to be low (Becerik-Gerber et al. 2012). Indeed, there is a lack of demand by clients for BIM models for FM (Australian Institute of Architects 2010) which is exacerbated by a general lack of collaboration between project stakeholders for modelling and model utilisation (Becerik-Gerber et al. 2012). The shortage of BIM skills and understanding in the FM industry hinders the adoption of BIM (BIM Task Group 2013).This is especially prominent because a BIM model for FM uses is considered an individual building asset, which requires continuous maintenance to remain valuable to the building itself and its owners (Becerik-Gerber et al. 2012).

Interoperability between BIM technologies and current FM technologies (e.g. CAFM – Computer Aided Facility Management) is still an issue in the handover of information and data to operation stage (Akcamete, Liu et al. 2011). Indeed, in existing buildings for example, FM legacy systems may be utilized for the next one or two decades. Unless the transfer of BIM data is automated, and the value of BIM is demonstrated, it is unlikely that facility managers can prove the business cases for using BIM in existing buildings. According to the British Institute of Facilities Management (2012) there is a need for open systems and standardised data libraries that can be utilised by any CAFM or asset management system. Without such non-proprietary format, facility owners and managers must enforce proprietary information systems or re-key information into a CAFM System. Owners and facility managers pay to have the data keyed into relevant FM systems (East and Brodt 2007). However, to date there is undefined fee structure for such an additional scope (Becerik-Gerber et al. 2012).

An information exchange specification called COBie (Construction Operations Building Information Exchange) was developed to provide a structure for the lifecycle capture and delivery of information needed by facility managers (East and Nisbet 2010). While there is an agreement that COBie is necessary for structuring data (Open BIM Network 2012), COBie "does not provide details on what information is to be provided, when and by whom" (East and Carrasquillo-Mangual, 2013, p.1). and there is still limited knowledge in the identification of such requirements. Only a brief summary of some non-geometric requirements was identified in recent studies (Becerik-Gerber et al. 2012). This challenge is best summarised by Teicholz (2013) who argues that *"Building information models delivered at project completion are a rich information source for FM, but not all of the information is valuable on a day to day basis within the broad range of an FM practice, where data retrieval, change management, and tracking costs and work activity are critical. Facility managers will need to detail and prioritise their information requirements".*

The lack of contractual and legal framework for the implementation of BIM in general (Eastman et al. 2011) and for BIM for FM in particular (Becerik-Gerber et al. 2012) is a significant area of challenges. For the foreseeable future, legal and liability requirements in the building industry will dictate that contracts between the parties be conveyed in the traditional written and two-dimensional graphical form (Reddy 2011). The first legal risk to determine is ownership of the BIM data and how to protect it through copyright and other laws (Azhar 2009).

Licensing agreements are a feasible option that allows limited use to another party while maintaining copyright and ultimate control (British Institute of Facilities Management 2012). However, this solution is challenged by the fact that there are difficulties with embedded data and 'whole of life' risk and audit (Australian Institute of Architects 2010). As a result, most contracts forms still require the handover of paper documents containing equipment lists, product data sheets, warranties, spare part lists, preventive maintenance schedules, and other information. This often leads to incomplete and inaccurate information that is difficult to access and utilise for the purpose of increasing FM efficiencies.

3. VALUE

Today most contracts require the handover of paper documents containing equipment lists, product data sheets, warranties, spare part lists, preventive maintenance schedules, etc. This information is essential to support the management of the facilities by the owner and property manager. The current process of information handover to FM phase is generally done manually. As a result, information handed over is often incomplete and inaccurate. The industry is spending millions of dollars, and thousands of man-hours recreating such information and working with inefficient workflows (Keady 2013). Of this $15.8 billion loss caused by interoperability inefficiencies, $10.6 billion are attributed to the owner/operator during the operations and maintenance phase of a building (Lee, An et al. 2012).

The improvement of handover processes is the among the main drivers for using BIM in FM (Gu, Singh et al. 2008). Despite current interoperability challenges, BIM data and information collected during the building lifecycle will reduce the cost and time required to collect and build FM systems (Teicholz 2013). For example, data regarding spaces, systems, finishes, etc. can be captured in digital format BIM models and do not require to be re-entered in downstream FM systems (Eastman et al. 2011). More importantly, the quality and reliability of data will improve, and in turn will result in increased workforce efficiencies (Teicholz 2013). According to Eastman et al. (2011) the utilisation of improved data quality is likely to improve further as more people become accustomed to working in a BIM environment. These benefits are summarised in a statement by the BIM Task Group (2013): *"BIM will provide a fully populated asset data set into CAFM systems and therefore reducing time wasted in obtaining and populating asset information enabling us to achieve optimum performance quicker, reduce running costs and refine target outcomes".*

The ability of extracting and analysing views from BIM models, specific to various needs and users, will provide information to make decisions and improve the delivery of facilities (Azhar 2011). There are also other benefits for FM, associated with the visualisation nature of BIM, compared to the two dimensional drawings (Akcamete, Liu et al. 2011). BIM visualisation provides accurate geometrical data that has never been possible before (CRC Construction Innovation, 2007). It enables the analysis of building proposals and the simulation and benchmark of building performance (Atkin and Brooks 2009). This is facilitated by the parametric nature and semantic richness of numerous types of relationships such as "is-contained-in", "is-related-to", "is-part- of", etc. that are very important in FM. Scenarios showing the benefits of BIM to FM interventions such as troubleshooting broken equipment and improving ergonomic and comfort conditions are described by Becerik-Gerber et al. (2012). Other important BIM in FM applications outlined in this study are in space management, emergency management, energy control and monitoring, and personnel training and development.

There are some proposals that adopting BIM in FM will facilitate the future involvement of facility mangers at a much earlier design stage to convey their input and influence the design and construction (Azhar 2009). Finally, the adoption of BIM in FM is expected to provide ways for managing knowledge about building operation which can be utilised in future designs (BIM Task Group 2013).

4. CASE STUDY

The research question posed at the start of this paper was to investigate the value and challenges of BIM in FM for new and existing assets. The value of BIM in FM for new assets has been explored in the literature review. However, there is also a need to explore how BIM can add value to existing buildings. A case study was collated and aimed to investigate the value of BIM in managing spaces selected as a specific FM function. The case study was conducted on Northumbria University's city campus, which is based in Newcastle upon Tyne (UK). It is made up of 32 non-residential buildings with a gross area of over 120,000 m² (Figure 1). The case study started in 2010, when the University commissioned five developers to produce building information models with a focus on improving the performance of space management. Working to a concise BIM Specification, the models were completed by the five developers in five weeks at a cost of approximately £ 0.33/m². Developers have used existing Estates Department's floor plans in DWG format, scans of the original elevations, sections in JPEG format, and space information in Excel databases. As the case study involves an existing asset, there are key challenges that the application of BIM for FM purposes should address. These are related to the strategic issues and the business case for migrating from the current FM processes to BIM-based FM processes. The case study involved personnel from the University's estates department who have taken part in detailed discussions investigating the value and challenges of BIM in managing the spaces of the existing university campus. The results are summarised into the following categories.

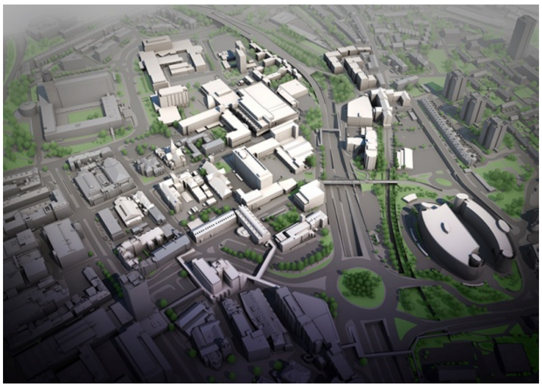


Fig. 1: Northumbria University's city campus

4.1 Workforce and process efficiencies

The efficiency of processes associated with managing spaces, such as updating geometric and non-geometric information, came immediately to the fore when the functionalities of BIM for FM were explored. The University currently updates its drawings and information in two separate environments (i.e. floor plan drawings in two-dimensional graphical representation - i.e. DWG format - and a database in MS Excel format). Both require manual update, creating duplication of workload. Photographs and scanned elevations and sections from the original drawing sheets are used to verify specific details. With regular changes in building utilisation occurring year round, this is a lengthy task requiring the full time attention of a CAD technician. Using BIM for FM the creation of geometric information and the inclusion of specific FM information allows automatic updating of required schedules; producing instant sections, elevations, three-dimensional visuals and renders, and generating drawing sheets from a single integrated environment. This provided efficiency gains that have not been possible to achieve with current processes and technologies utilised by the FM team (Figure 2). It was estimated that this would reduce the need for a full time CAD technician and provide cumulative savings from improved efficiencies in future work orders over the years. In addition, the BIM models' data richness provided additional information relating to statutory compliance such as integrated asbestos register, emergency equipment, escape routes, accessibility and essential maintenance. Detailed information on these components can be easily traced, updated and reported in schedules. An example that includes an area of asbestos, properties of the asbestos type, its exact location, date of removal and location of survey documentation can be displayed in real time (Figure 4). Moreover, the estate department staff identified that BIM for FM models, with the augmentation of available technology functionalities, to enable services such as room finding, fault reporting, development and refurbishment option generation, and assessment of building performance. Such services lead to reduction in response times, with detailed campus knowledge assigned to specific buildings, levels, rooms, etc. For example, with each request to replace a light bulb on the campus, the maintenance staff could check in real time the bulb type and manufacturer using the FM model before carrying out the task. Another example could be to check the paint colour code for a room where the wall finish has been damaged, thus saving staff time and material resources. The models have been used to trial option appraisal for redevelopment and refurbishment as phased plans, sections, elevations and 3D rendered views that could be quickly displayed and assessed (Figure 5). This provided time and costs associated with design and more accurate representations for strategic decision making from a management perspective.

4.2 Accuracy of records of geometric information

The creation of BIM models have revealed that some areas of buildings on the campus failed to line up when the two dimensional drawings and elevation scans were used as a basis to build the models (figure 5). This has called upon the estate department to order new surveys to verify the building layout. It was also agreed that once the FM team achieve the required BIM skills, the maintenance of geometric records will be accomplished in a more efficient way from both economic and quality perspective.

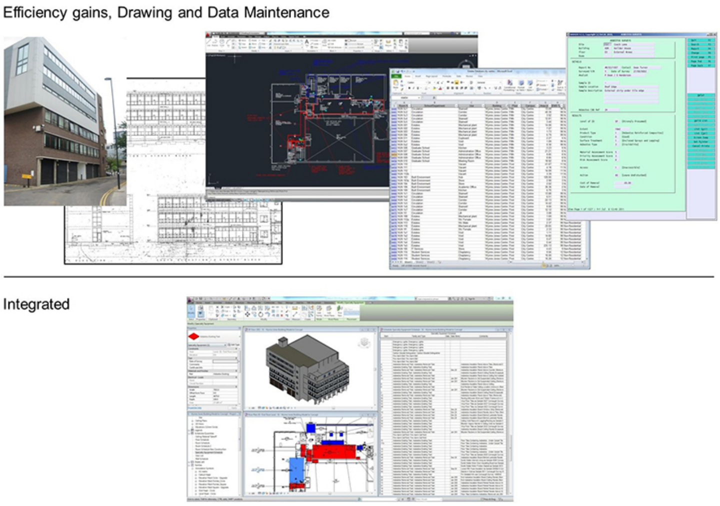


Fig. 2: Comparison of existing data maintenance processes with BIM processes

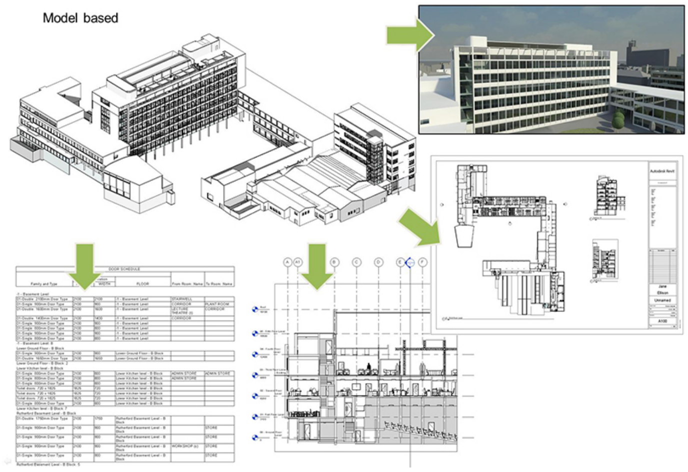


Fig. 3: Single BIM integrated database as a trusted source for information

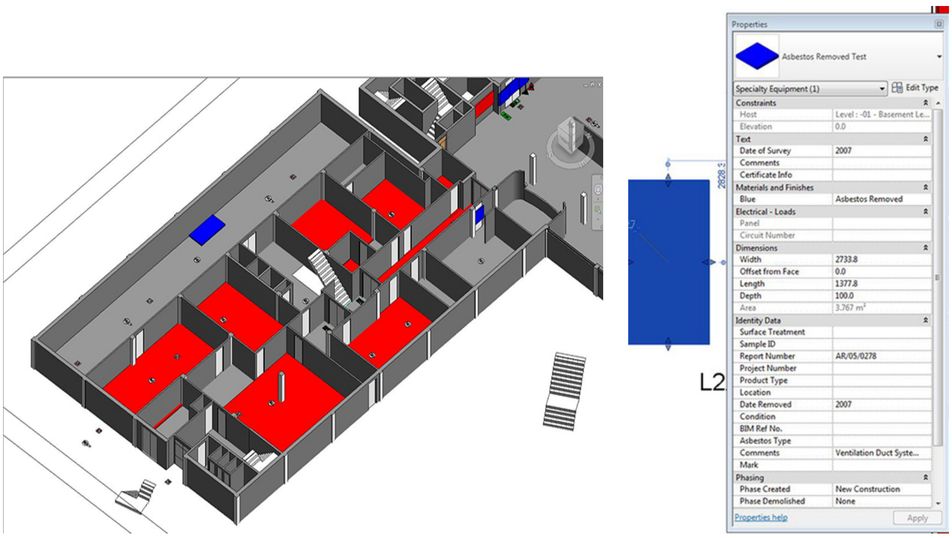


Fig. 4: 3D view of removed (blue) and existing (red) asbestos in building model

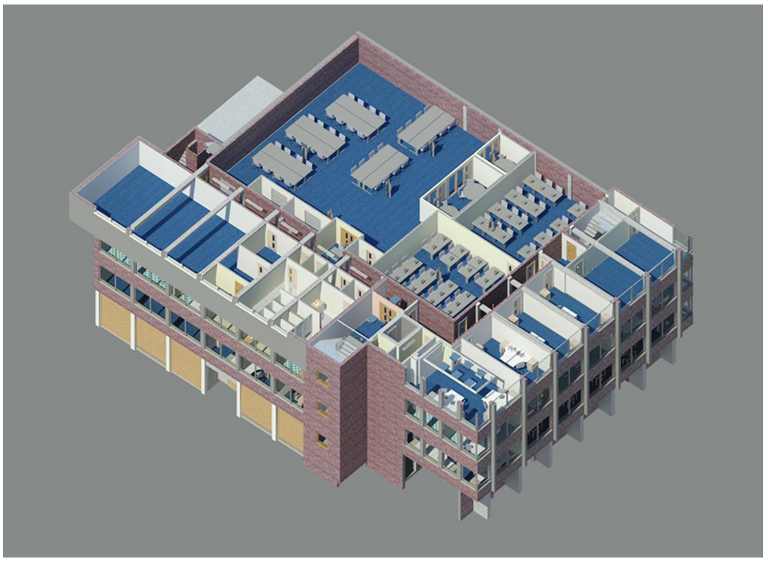


Fig. 5: Generation of design options for internal refurbishment

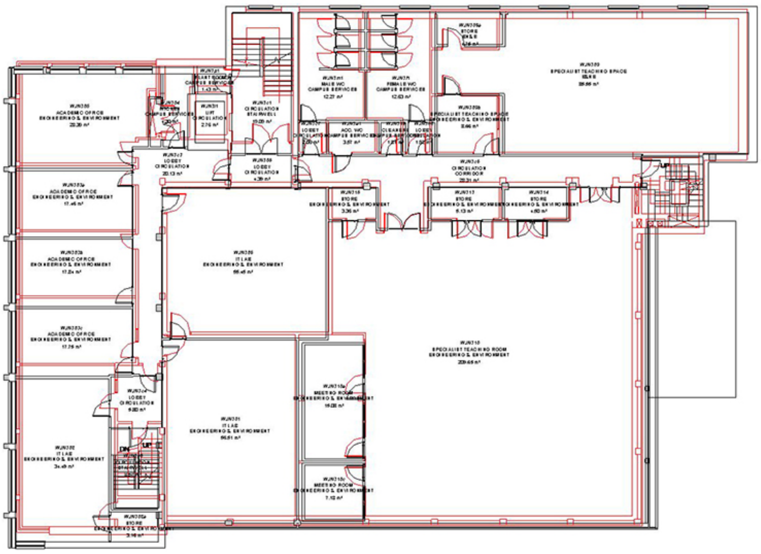


Fig. 6: Improved accuracy of building records when tested in BIM (Red: original, Black: updated)

4.3 Implementation challenge and maintenance of models

Once the previously illustrated scenarios have demonstrated the value of BIM in FM, discussions with the FM estates department have shifted to understand the challenges associated with migrating from current FM processes to BIM based processes. Several key challenges were revealed and are related to the implementation. There is a need to communicate and understand the benefits of BIM for FM such as the examples previously mentioned. However the FM team should have the skills to be in position of maintaining and controlling the BIM for FM models. A concise BIM for FM specification must be developed to define the information required to suit the particular requirements of the business and FM function. It was also acknowledged that there are still industry-wide challenges related to technologies and processes. FM teams wishing to implement BIM for FM in the immediate future should be willing to adapt to such challenges. For example, one of the major concerns was the limited compatibility between BIM technologies and FM technologies (e.g. CAFM, BAS, etc.) which can be exacerbated by the huge difference among the lifecycle of BIM technologies, FM technologies and buildings. The lifecycle of a BIM technology is typically 12 - 24 months, whereas the lifecycle of FM legacy systems vary between 10 - 20 years and building lifespan could be up to 100 years. This means that data standards and interoperability will remain critical for the adoption of BIM for FM technologies. Therefore, FM organisations wishing to implement BIM for FM in the immediate term should take a long term view (e.g. minimum 5 years) and be willing to work with different standards and information formats. It was also identified that due to the evolving nature of the BIM for FM field, and the differences in the lifespans of technologies, FM organisations must not fit their FM business processes to suit a particular technology which would otherwise result in a continuous effort of adaptation. However, FM organisations can presently attain the benefits of BIM for FM through the development of a tailored BIM specification and templates (e.g. information to be included, level of detail, object styles, line styles, units, export settings, etc.) that suit their particular business requirements. Examples of levels of development used in the case study are reported in figures 7 and 8 using the AIA LODs (AIA, 2012). Such specifications and template will also help to engage with the supply chain on future work on the university campus and enable compatibility with the organisation's FM procedures.

Fig. 7: a BIM model at AIA LOD 500 (left) and AIA LOD 100 (right)

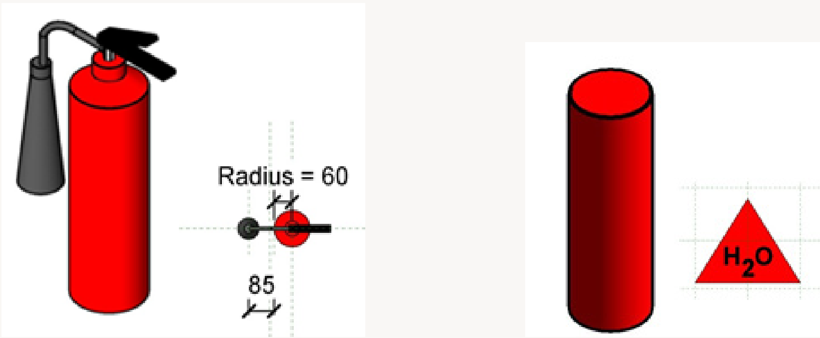


Fig. 8: Fire Extinguisher model at AIA LOD 500 (left) and AIA LOD 100 (right)

5. CONCLUSION

BIM applications have been thoroughly discussed and researched at planning, design and construction phases. BIM in FM application is still considered an emerging field. The understanding of the challenges and value-adding potential of BIM in FM is fundamental at this early stage. In this paper, such an investigation, utilising two research methods that build on each other – i.e. review of existing studies and a case study approach – was conducted. The findings from the literature review provided evidence that there is agreement about the value and potential of BIM in FM. It demonstrated that the value of BIM in FM stems mainly from:

- Improvement to the current manual processes of information handover; improvement to the accuracy of FM data
- Increase of the efficiency of work orders execution, in terms of speed, to accessing data and locating interventions. Such value is derived from the capability of BIM to provide a data-rich visual and integrated data environment.

However, there are challenges that are hindering the exploiting of BIM in FM. Four main challenges are:

- The lack of tangible benefits of BIM in FM despite agreement about the potential of BIM in FM
- The interoperability between BIM and FM technologies
- The lack of clear requirements for the implementation of BIM in FM
- The lack of clear roles, responsibilities, contract and liability framework.

Other challenges are related to the procedural and cultural mindset in the industry where FM managers are involved only at a very late phase in the project and models are not updated with as-built information. Another key finding is the lack of real-world case studies of BIM applications in FM. A real world case study of 32 non-residential buildings with a gross area of over 120,000 m² was presented with the following objectives in mind:

- Add a contribution as a real world case study;
- answer some of the challenges identified and in particular demonstrate the value of BIM in FM;
- Clarify the challenges associated with migrating to BIM-based FM;
- Reveal potential new challenges.

The results from the case study demonstrate with practical examples how BIM can add benefits to the workforce and process efficiencies and to the accuracy of records of geometric information. In addition to the challenges identified in previous literature, discussion with estate department experts conducted during the case study revealed a further challenge which is inherent in the significant differences of lifespans BIM technologies, FM technologies and buildings. This means that FM organisations must be prepared to work with different information and data standards in the mid and long terms instead of adapting their business processes to fit a specific technology. It is suggested that the development of a BIM for FM specification that suits the need of the organisation's FM processes is currently key to exploit the benefit of BIM-based FM and enable the organisation and its supply chain to work according to structured FM processes.

6. REFERENCES

AIA (2012). *E203: Building Information Modeling and Data Exhibit*. The American Institute of Architects, Washington, DC, U.S.

Akcamete, A., et al. (2011). Integration and visualization maintenance and repair work orders in BIM: lessons learned from a prototype. *Proceedings of the 11th International Conference on Construction Applications of Virtual Reality*, 3-4 November 2011, Weimar, Germany.

Atkin, B. and A. Brooks (2009). *Total facilities management* (3rd Ed.). Chichester, UK: Wiley-Blackwell.

Australian Institute of Architects (2010). *BIM in Australia*. Australian Institute of Architects, South Melbourne, Victoria, Australia.

Azhar, S. (2011). Building Information Modeling: Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, vol 11 (3), pp. 241-252.

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G. (2012). Application areas and data requirements for BIM-enabled facilities management. *Journal of construction engineering and management*, vol 138 (3), pp. 431 - 442.

BIM Task Group (2012).*The Government Soft Landings Policy*. http://www.bimtaskgroup.org/gsl-policy-2 (last accessed Apr 5th, 2013).

BIFM (2012). *BIM and FM: Bridging the gap for success*, British Institute of Facilities Management, Bishop's Stortford, Hertfordshire, UK.

East, W.E. and Carrasquillo-Mangual, M. (2013). *The COBie Guide: a commentary to the NBIMS-US COBie standard*, Engineer Research and Development Center, Champaign IL, U.S.

East, E. W. and N. Nisbet (2010). Analysis of life-cycle information exchange. *Proceedings of the International Conference on Computing in Civil and Building Engineering*, W. TIZANI (Editor), 30 June-2 July, Nottingham, UK.

East, W. and W. Brodt (2007). BIM for construction handover. *Journal of Building Information Modeling*, 2007, pp. 28-35.

Eastman, C., Teichloz, P., Sacks, R. and Liston K. (2011). *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors (2nd Ed.)*, New Jersey, U.S.: Wiley.

Gu, N. and K. London (2010). Understanding and facilitating BIM adoption in the AEC industry. *Automation in Construction*, vol 19 (8), pp. 988-999.

Gu, Ning and Singh, Vishal and London, Kerry and Brankovic, Ljiljana and Taylor, Claudelle (2008). Adopting building information modeling (BIM) as collaboration platform in the design industry. In: CAADRIA 2008: Beyond Computer-Aided Design : *Proceedings of the 13th Conference on Computer Aided Architectural Design Research in Asia*, 9-12 April, 2008, Chiang Mai, Thailand.

HM Government (2013). *Building Information Modelling Industrial strategy: government and industry in partnership*, London, UK.

Keady, R. A. (2013). Financial Impact and analysis of equipment inventories. Facilities Engineering Journal, http://www.fmlink.com (last accessed June 5th, 2013).

Khemlani, L. (2011). BIM for Facilities Management, AEC Bytes, http://www.aecbytes.com (last accessed June 6th, 2013).

Kincaid, D. (2004). *Adapting buildings for changing uses: guidelines for change of use refurbishment*, London and New York: Taylor & Francis.

Lee, S., An, H., and Yu, J. (2012). An Extension of the Technology Acceptance Model for BIM-Based FM. *Construction Research Congress,* 2012, pp. 602-611.

Open BIM Network (2012) *Open BIM* Focus – COBie, issue 4, Oct 2012.

Reddy, K. P. (2011). *BIM for building owners and developers: making a business case for using BIM on projects*, New Jersey, U.S.: John Wiley & Sons.

Spedding, A. and R. Holmes (1994). *CIOB Handbook of Facilities Management*, Harlow: Longman Scientific & Technical.

Teicholz, P. (2013). *BIM for Facility Managers*. New Jersey, U.S.: John Wiley & Sons.

PART III: BIM & VR: SITE APPLICATIONS

PRACTICAL APPLICATIONS OF 3D/4D MODELING, AND PROCESS SIMULATION IN CONSTRUCTION

Yang Zhang, Mohammed Al-Bataineh and Jesse Kostelyk
S.M.A. Consulting Ltd., Edmonton, Alberta, Canada

Simaan AbouRizk
University of Alberta, Edmonton, Alberta, Canada

ABSTRACT: *This paper covers the application of innovative decision support technologies on two major projects in Edmonton. The first one is the West Edmonton Sanitary Sewer (WESS) stage W12. A syphon was constructed to connect the Rat Creek Trunk to the Gold Bar Wastewater Treatment Plant across the North Saskatchewan River, which was designed to control and reduce the combined sewer overflow. The other one is the 3.3-km North LRT (Light Rail Transit) extension line, which connects the current Churchill station to the future NAIT station in Edmonton. A tunnel excavated using the Sequential Excavation Tunneling Method from Churchill station to MacEwan station in the downtown area plays a critical role in the overall project, and has significant impact on project completion date and project budget. Due to the complexity of the two projects, various 3D technologies and construction simulation models were applied to facilitate decision-making processes and project controls. 3D models were developed for design review and design conflict detection, while 4D models were established to help create a robust construction schedule. Construction sequencing animation was used to convey design intents and demonstrate construction stages to contractors and workers. Construction simulation models were developed in order to analyze different scenarios and assist in selecting the best option. The combined applications of 3D technologies and construction simulation helped the project team to identify critical issues, and assured effective communication among engineers, management, contractors, and other parties. Therefore, it provided better opportunities for the success of the projects.*

KEYWORDS: *Construction management, drainage construction, design review, 3D modeling, construction simulation, animation*

1. INTRODUCTION

In general, large-scale, complex, unique construction projects bring significant difficulties and challenges to management, engineers, designers, contractors, workers and other project stakeholders.
These projects involve day-to-day problem solving dealing with design, construction and project management issues. High quality and efficient decision making increases the chance of project success. This paper introduces the practical application of 3D/4D modeling and construction simulation technologies which provided decision-making supports on two multi-million-dollar projects in Edmonton, Alberta, Canada.

The first project is the West Edmonton Sanitary Sewer (WESS) stage W12. The Rat Creek outfall was targeted as part of the West Edmonton Sanitary Sewer project. WESS W12, a syphon connecting the Rat Creek combined trunk to the South Highlands Interceptor, was designed to take overflow and convey it safely to the Gold Bar Wastewater Treatment Plant on the south side of the river. This was expected to reduce the CSO discharges into the North Saskatchewan River by over 70%, significantly improving water quality. Ultimately, the syphon would convey all flow from the 7 km of West Edmonton Sanitary Sewer project to the Gold Bar Wastewater Treatment Plant for treatment. Flow would be controlled by the Real Time Control (RTC) No. 3 structure located deep beneath the city streets. Associated Engineering was the designer for the project.

The other project is the 3.3-km North LRT (Light Rail Transit) extension line, which connects the current Churchill station to the future NAIT station in Edmonton. A tunnel excavated using the Sequential Excavation Tunneling Method from Churchill station to MacEwan station in the downtown area plays a critical role in the overall project, and has significant impact on project completion date and project budget.

Citation: Zhang,Y., Al-Bataineh, M., Kostelyk, J. & AbouRizk, S. (2013). Practical applications of 3D/4D modeling, and process simulation in construction. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Due to the complexity of these two projects, various 3D technologies were applied to facilitate decision-making processes. 3D models were developed for design review and design conflict detection, while 4D models were established to help create a robust construction schedule. Construction sequencing animation was used to convey design intents and demonstrate construction stages to contractors and workers. Construction simulation models were developed in order to analyze different scenarios and assist in selecting the best option. The combined applications of 3D technologies and construction simulation helped the project team to identify critical issues, and assured effective communication amongst engineers, management, contractors, and other parties. Therefore, it provided better opportunities for the success of the projects.

The remainder of the paper is organized into the following sections. The previous research efforts related to 3D/4D modeling are reviewed. In the section for the WESS W12 project, the project background and major challenges are introduced. That is followed by the application of construction simulation approach for selecting the best construction option and the design and constructability review using 3D models. In the section for the NLRT project, the design and construction review method is depicted, followed by the details of 4D modeling and visualized earned value analysis.

2. LITERATURE REVIEW

The application of 3D and 4D technologies as a supplement to the traditional design, project control, team communication processes would help identify design conflicts, reduce rework and prevent construction incidents (Haque and Rahman, 2009). 3D/4D applications were reported by researchers which indicate that 3D/4D models can facilitate design and construction communication and problem identification, generate and optimize crane motion paths in a visualization environment, represent construction processes, enable time-space analysis, assist cut and fill calculation for earth work, etc (Hartmann and Fischer, 2007; Chi and Kang, 2010; Sampaio et al., 2010; Akinci et al., 2002; Shah et al., 2008). For underground utility construction, Kraus et al. (2007) indicate that the early identification of interference of the existing and proposed utilities is critical for timely project delivery.

3. WEST EDMONTON SANITARY SEWER W12 PROJECT

3.1 Project overview

The construction of the WESS W12 project proved to be extremely challenging; its environmentally sensitive location in the river valley as well as its extreme depth – 70 meters below downtown Edmonton – was understood. However, the geotechnical investigation revealed that almost the entire project was situated within the footprint of abandoned coal mines. Five deep shafts would have to be constructed in ground laden with coal seams, water pockets, and voids, with the detection of methane gas under pressure in several locations. The tunnel alignment would run between two coal seams. Access was also severely limited: the northern construction site was on Jasper Avenue; the main thoroughfare is through Edmonton's downtown; and most of the alignment was under the Riverdale Golf Course and the river itself.

Due to the uncertain ground conditions and other constraints, the City Drainage Design and Construction crews initially planned to work with a newly-acquired LOVAT Earth Pressure Balance tunnel boring machine, using bolted segmental liners – the best technology for the job, but not one the City of Edmonton crews are familiar with. The deep shafts meant delays in removing soil and supplying construction materials, and shaft placement was limited. Finally, construction of the RTC3 structure required tying in to a fragile, very old 3200 mm pipe, under live flow. This pipe was the current combined trunk, with flow of 3.7 m/s in dry weather, and the potential for even higher velocities if one of the sudden rainstorms common to the area happened – a major safety concern. Operation of the tunnel would also be challenging. The tunnel itself would have to meet zero-infiltration standards due to the sensitive location, and the complex RTC3 structure would need to function without flaw to avoid flooding basements upstream or pouring unnecessary CSO into the river.

3.2 Selecting the best option based on simulations

In the planning stage, three options for placement of work shafts were identified through risk and value engineering workshops in 2004. The first was to place the working shaft at 85th St and proceed with excavation to McNally (Refer to Fig. 1). The second was the reverse: the work shaft would be placed at McNally, and therefore, the excavation would proceed from McNally to 85 St (at a negative slope and in the presence of water). The third option made use of a third shaft, placed in Dawson Park. In this option, tunneling proceeded to 85 St. The tunnel boring machine was then relocated to the Dawson shaft and excavation proceeded to McNally. Excavation of the Dawson shaft and the tunnel can proceed parallel to the excavation of the two shafts at 85 St and McNally.

Three discrete event simulation models were developed in Simphony (AbouRizk and Mohammad, 2000) to support the decision of which tunneling sequence to use. The details of construction processes, material handling, and resource constraints were modeled and simulated. Tunneling from 85 St to McNally or vice versa would require a material handling process roughly 80m deep, which impacted productivity significantly in simulations.

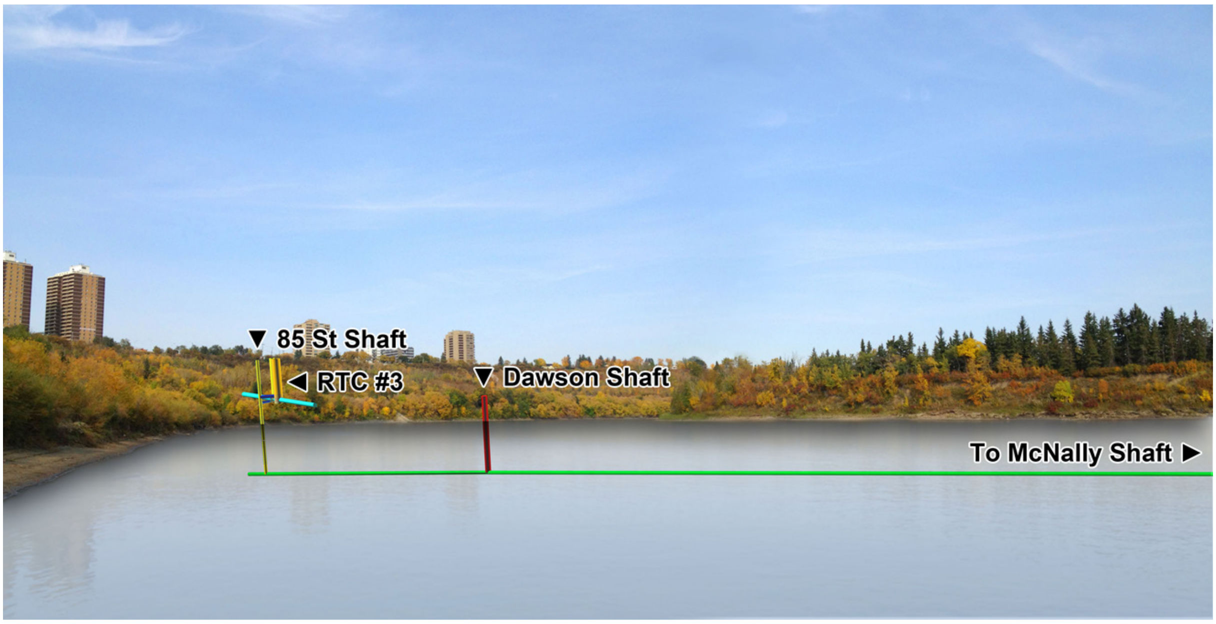


Fig. 1: Overview of the WESS W12 project

After a risk and cost-benefit analysis of all three options, the preferred option was determined to be two-way tunneling. This option had the least amount of risk associated with it, both in total value of calculated severity and in terms of risk factors that were considered "important" or higher. In addition, an 80m shaft would require a specialty hoist, with no redundancy, as no other equivalent hoist or crane is available in the city. The Dawson shaft uses hoisting technology that is readily available and can be replaced in a reasonable amount of time when required. Compounding the hoist issue, excavation from 85 St requires completion of the 85 St shaft prior to commencement of tunneling, so any delays during shaft excavation—which would be likely, given the depth—would delay the entire project. Excavating from Dawson requires only the 40m Dawson shaft, and allows the other two deeper shafts to be constructed with a greater degree of float. Finally, an analysis of expected costs and schedule (including risk) indicated that two-way tunneling was less expensive and likely to have shorter project duration.

Discrete event simulation scenarios were also developed to support the decision of what type of secondary liner to use in the tunnels. The choices were cast-in-place concrete, precast pipe sections, steel pipes with lining, or HOBAS pipe. Through consultation with the project team and a review of relevant literature, various assumptions were made: shift length, tunnel length, average production, distance between pumping wells, duration of concrete pouring activities, duration for track installation, time for grouting, and so forth.

The simulation models were developed, tested, and run. The simulation results showed that the total duration for cast-in-place liners was 220 days. If precast pipe sections were used, the duration was 204 days; steel pipes with lining were 184 days; and HOBAS pipes were 172 days.

A value analysis workshop was then conducted to discuss these choices, employing the Analytical Hierarchy Process (AHP) as the decision-making platform. The results of the AHP led to the selection of HOBAS pipes as the option with the best value, as not only was it the most schedule-friendly and one of the most maintainable and efficient options, it was also the most constructible. HOBAS pipes were installed as a secondary liner for the entire tunnel by the end of 2009, and their performance has been very satisfactory. Pressure tests have confirmed zero exfiltration for the tunnel.

3.3 Design and constructability review using 3D models

3D models of individual components of the structures to be built are constructed in CAD software to the exact specifications provided by the design/drafting team. As in the real structure, the model components can then be arranged into substructures, and those are subsequently constructed or assembled into structures of increasing complexity. We then employ additional modeling software to manage the model components, their arrangement, and their sequence in a construction context, giving the visualization a fourth dimension: time. Video replay of a construction sequence is an invaluable discussion tool.

The design team identified five options as being feasible construction options for the configuration of the three RTC No. 3 shafts (Fig. 2) that satisfied the required diversion and the intended hydraulic design. In order to select the best option, a structured selection process was facilitated based on value analysis, constructability reviews, and risk analysis. Value analysis was used to identify the options with a high value and present them for further analysis. Constructability reviews were conducted to understand the construction process and the construction challenges. After that, risk analysis was undertaken to identify and evaluate the option's risk and integrate that risk value in the selection process. This value analysis led to the initial decision to proceed with a two-shaft option, on the alignment but with a bypass and a "bulkhead shaft."

However, there were safety and technical feasibility concerns with the process of lowering the bypass bulkhead through the RTC No. 3 shaft, horizontally through the back tunnel, and then vertically into place in the existing 3200mm tunnel under live flow conditions. There were also grave concerns with entering the existing tunnel to anchor the bottom part of the bulkhead to initiate bypass of the flows. These same concerns would come into play when it was time to remove the bypass bulkhead.

In order to provide a clearer understanding, a 3D visualization of the RTC structure was generated and was used to create a 4D visualization depicting the construction sequence of the RTC structure as it was proposed. The animations generated were an invaluable visual aid, allowing decision-makers to see the process taking place without ambiguity.

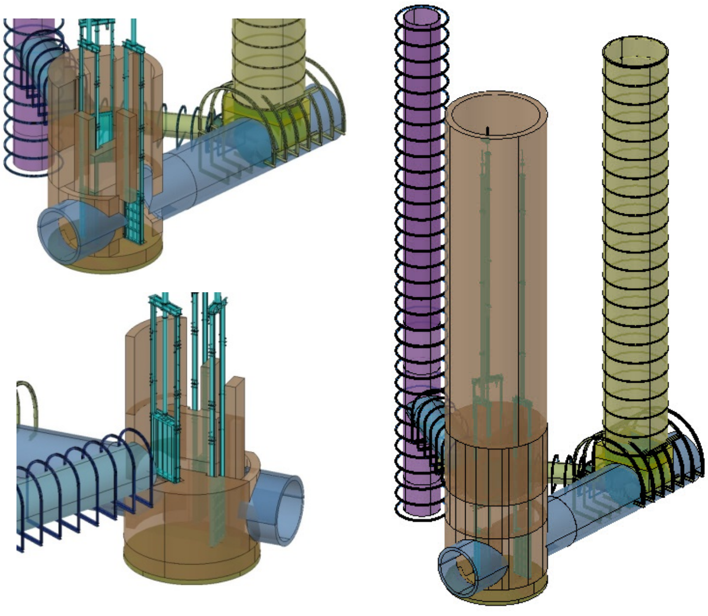


Fig. 2: Real Time Control (RTC) No. 3 structures – Top left: RTC No. 3 Shaft; Bottom left: RTC No. 3 Gates; Right: Overall of the RTC No. 3 Shaft

After reviewing the visualization, it was decided that the bypass bulkhead should be installed vertically through another shaft. The bypass bulkhead would extend vertically above the existing 3200mm tunnel and be held in alignment during installation and removal by channels forming slots in the bulkhead shaft. The bypass bulkhead would be installed near the center of the bulkhead shaft to allow entry to fix the bulkhead to the liner of the existing

3200mm tunnel. This would also allow for monitoring for leakage between the bypass bulkhead and the safety bulkhead and for pumping out any leakage.

The construction of the project was completed in 2011 and the tunnel is now in operation, successfully conveying flow to Gold Bar Wastewater Treatment Plant. The initial budget and schedule underwent two revisions due to external events, construction challenges, and additional scope, and totaled $44 million. Zero exfiltration was confirmed by pressure tests. Two CEA (Consulting Engineers of Alberta) showcase awards under two different categories were announced to recognize the successful application of 3D/4D and construction simulation technologies on the W12 project.

4. NORTH LIGHT RAIL TRANSIT EXTENSION PROJECT

4.1 Project overview

The North Light Rail Transit (NLRT) extension project is to construct an extension line for the existing LRT transportation system in downtown Edmonton, Alberta, Canada. The total length of the extension line is 3.3 km. The features of the project include three new stations – MacEwan, Kingsway, NAIT, underground connections between MacEwan Station and Churchill Station, Street-level LRT between 105th Ave and NAIT, and Relocation of Kingsway bus terminal at Royal Alexandra Hospital. The project was started in 2011and planned to be completed in 2014. The total project budget is estimated at $755 million.

The major challenges of the project can be summarized in the following. First, brown field construction involves relocation of existing utilities and drainage and coordination of existing and proposed utilities and drainage. The currently used 2D approach cannot effectively handle the massive information, and it caused inefficient communication, inconsistent representation, and hard-to-discover design conflicts. Second, the construction of the big curved LRT tunnels connecting the existing Churchill station to the new MacEwan station in downtown Edmonton; as it is on the critical path of the project, monitoring the tunneling progress became important. Finally, the overall monitoring and controlling of the project, which involves more than twenty disciplines in an intuitive way, became difficult. Traditional scheduling and reporting approaches cannot reveal the geographical based inter-relationships of work packages. 3D approaches were applied to improve the current practice either in design review or project control.

4.2 Design and construction review

Linear transportation construction involves not only the above ground construction but also the underground utilities and drainage along the right of way. In order to satisfy the clearance requirements in which distances are measured based on the track alignments, existing utilities and drainage in the clearance zone need to be removed. New utilities and drainage are proposed to replace the removed ones and also to meet the requirements of the new LRT line. Due to the limitation of area in downtown Edmonton, underground utilities and drainage constitute several complicated networks which make utility design a time-consuming and tedious task.

2D drawings and utility matrix are the major utility design tools in current practice, although 3D/BIM (Building Information Modeling) tools are becoming more and more prevalent in building design, structure design, road design, track design, etc. Fig. 3 shows the typical utility drawings for Kingsway station. The 2D approach has the following disadvantages. 1) Missing utilities on cross sections. Cross sections are generated at certain intervals. While utilities run between two cutting planes and do not intersect with the cutting planes, they are not easily captured by the cross sections. 2) Inefficient elevation representation. Elevations or depth of utilities from ground surface are not represented on plan views. It requires the users' translation to generate virtual 3D models in mind by referring to the cross section views at specific locations, which is hard for most project participants due to the complexity of utilities resulting in poor communication. 3) Unified-width lines do not reflect actual sizes of utilities on plan drawings. Unified-width lines are used to represent utility layout on plan drawings. For utilities that are large width-wise, potential design conflict might not be able to be identified until late stage construction. 4) Lack of communication with other disciplines. 2D drawings are not efficient to communicate the design of utility relocation. Thus, it becomes an obstacle in the multiple discipline design review process.

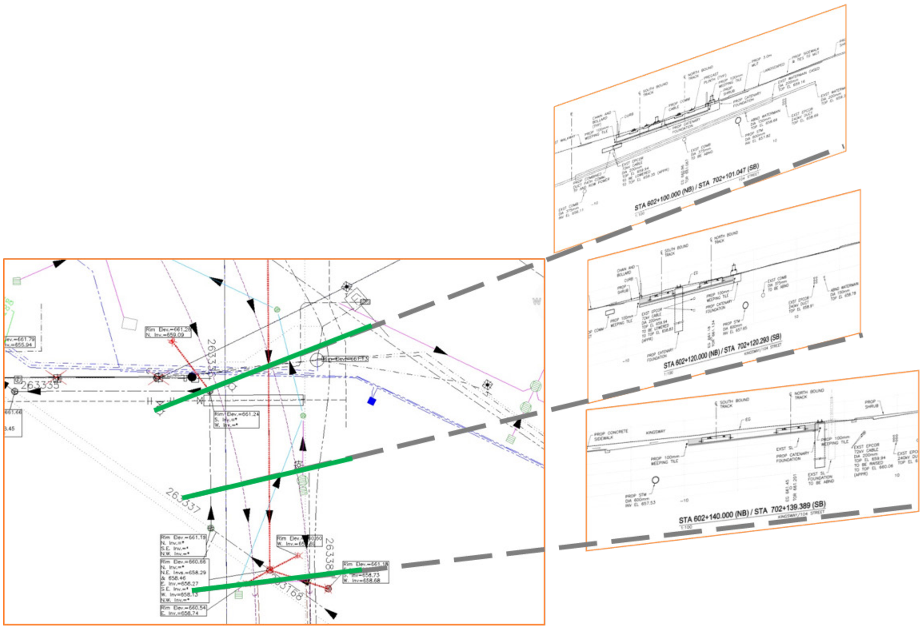


Fig. 3: Typical Utility Drawings in Plan and Cross Section View at Kingsway Station

In order to deal with the above-mentioned drawbacks, the project team decided to adopt the 3D approach to review design drawings before the utility relocation work began. 3D models of electricity, gas, water, cable, traffic signals, communication, drainage, duct bank, and foundation were generated. The models were imported to Navisworks and reviewed. Dozens of design conflicts were identified, and one of the major ones is at the Kingsway station. A proposed communication duct bank clashed with a proposed sewer line and an existing drainage pipe. The timely design conflict identification avoided construction delay and saved project cost. Fig. 4 shows the 3D models and identified design conflicts.

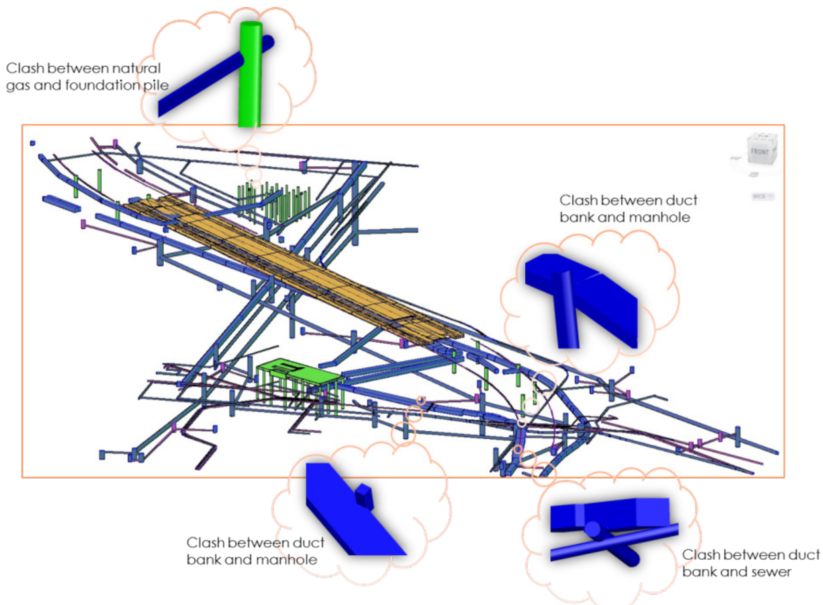


Fig. 4: 3D Models and Identified Design Conflicts at Kingsway Station

4.3 Project control using 3D technologies

4D construction visualization was introduced as a supplement to the traditional project control tools, such as bar chart and Gantt charts. A 4D model integrates the 3D models of physical work packages with the construction schedule. The work under construction is represented in Green. As a linear project, construction work is distributed in different geographical locations. The visualization of the work can help the project team coordinate work by location. It can also help verify the accuracy of activity relationships and logic. Fig. 5 demonstrates the construction of Kingsway station.

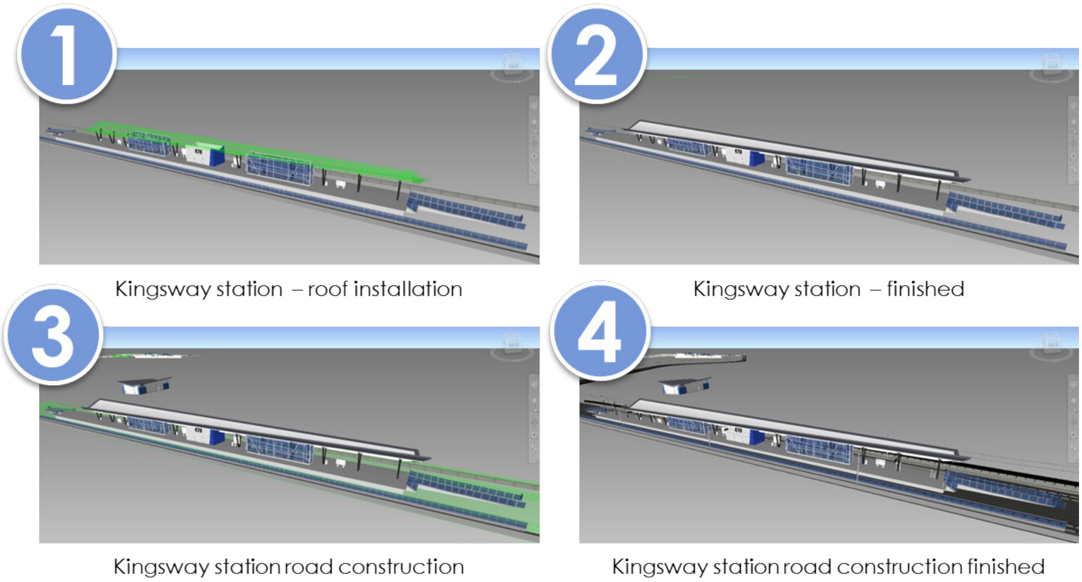


Fig. 5: Construction Visualization of Kingsway Station

Earned value analysis is widely adopted in the industry to monitor the performance of project schedule and cost. SPI (Schedule Performance Index) and CPI (Cost Performance Index) are two indices reflecting the project performance. The indices are equal to or greater than zero. The higher the value, the better the performance is. In order to position the most important issues based on earned value analysis (EVA), color codes were defined as follows, Pink: 0-0.5; Red: 0.5-0.85; Yellow: 0.85-1.0; and Green: equal or greater than 1.0. A customized data column was created to store the EVA color codes. It enables Navisworks to read and present the EVA status in 3D. Areas with poor performance bring immediate attention (Fig. 6).

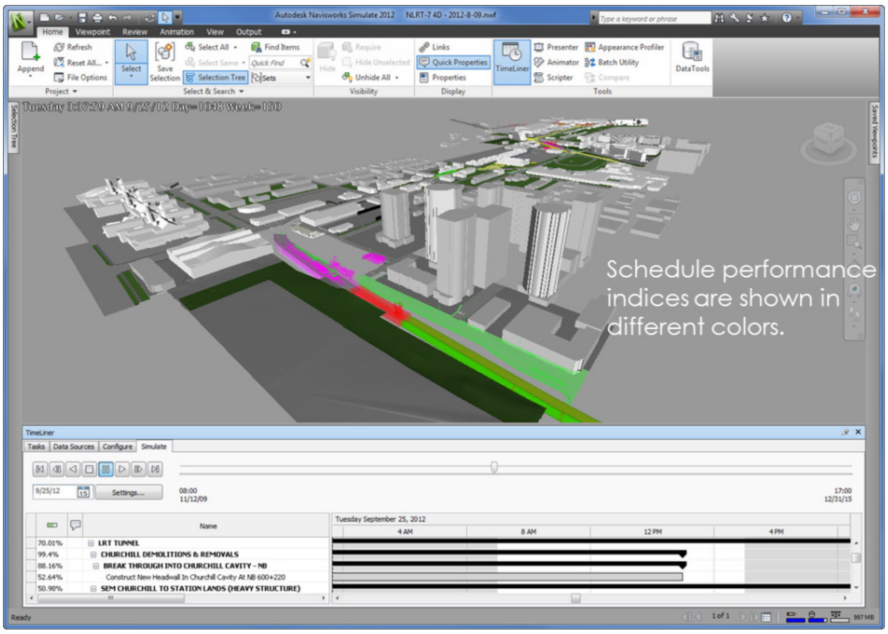


Fig. 6: Earned Value Analysis Status Shown in 3D

5. CONCLUSION

The combined applications of 3D technologies and construction simulation helped the project team to identify critical issues, and assured effective communication among engineers, management, contractors, and other parties. Therefore, it provided better opportunities for success of the projects.

6. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the City of Edmonton and AECOM for their extensive collaboration.

7. REFERENCES

AbouRizk S.M. and Mohammad Y. (2000). Simphony-An Integrated Environment for Construction Simulation, *Proceedings of WSC 2000*, Orlando, Florida, pp.1907-1914.

Akinci B., Fischer M., and Kunz J. (2002). Automated Generation of Work Spaces Required by Construction Activities, Journal of Construction Engineering and Management, Vol. 128, No. 4, 306-315.

Chi H. L., and Kang S. C. (2010). A physics-based simulation approach for cooperative erection activities, Journal of Automation in Construction, Vol. 19, No. 6, 750-761.

Haque M. E. and Rahman M. (2009). Time-Space-Activity Conflict Detection Using 4D Visualization in Multi-storied Construction Project, Proceedings of First International Visual Informatics Conference, 266-278.

Hartmann T., and Fischer M. (2007). Supporting the constructability review with 3D/4D models, Journal of Building Research & Information, Vol. 35, No. 1, 70-80.

Kraus E., Quiroga C., Brown R., Stevens C., and Koncz N. (2007). Development of A Utility Conflict Management Tool, Texas Transportation Institute, Report 0-5475-1.

Sampaio A. Z., Ferreira M. M., Rosário D. P., and Martins O.P. (2010). 3D and VR models in Civil Engineering education: Construction, rehabilitation and maintenance, Journal of Automation in Construction, Vol. 19, No. 7, 819-828.

Shah R. K., Dawood N., and Castro S. (2008). Automatic Generation of Progress Profiles for Earthwork Operations using 4D Visualisation Model, Electronic Journal of Information Technology in Construction, Vol. 13, 444-459.

PASSIVE RFID-BASED ASSET TRACKING AND PROJECT MANAGEMENT ON A LARGE HOSPITAL PROJECT

Aaron Costin, Audrey Shaak, Jochen Teizer
RAPIDS Construction Safety and Technology Laboratory, School of Civil and Environmental Engineering, Georgia Institute of Technology, 790 Atlantic Dr. N.W., Atlanta, GA 30332-0355

George Pfeffer, Atul Khanzode, Durga Saripally, Osman Chao
DPR Construction, 1450 Veterans Boulevard, Redwood City, CA, 94063

Bernd Schoner, Satyan Shah
ThingMagic, Cambridge Center, Cambridge, MA 02142

ABSTRACT: *As construction job sites get larger and more complex, the need to increase building protocol control and safety is becoming more necessary. Having a real-time tracking system for materials, equipment and personnel of a job site will help project managers to enhance the safety, security, quality control, and worker logistics of a construction project. In this paper we will present the method of integrating Radio Frequency Identification (RFID) and Building Information Modeling (BIM) for real-time tracking of materials, equipment, and personnel. The purpose is to generate real-time data to monitor for safety, security, quality control, and worker logistics, and to produce leading indicators for safety and building protocol control. The concept of reference tags will be utilized along with a cloud server, mobile field devices, and software to assist the project managers with staying connected with the job site, from supply chain management to installation. Hardware components include RFID tags, portal RFID readers, fixed turn-style readers, and mobile handheld devices. The system was deployed on a 900 thousand square feet hospital project that consisted of three major buildings, 125 contractors, and 1,200 workers. Preliminary results show that the integration of these technologies enhances productivity, reduces scheduling issues, assists in subcontractor management, and provides real-time information on deployed crews and building activities. High-level metrics have been developed at the project and large contractor level. Additionally, the system also provided real-time information on local worker participation as part of the project goal. Based on experimental analysis, we demonstrate that the RFID and BIM system is a practical and resourceful tool to provide real-time information and location tracking to increase safety, security, and building protocol control.*

KEYWORDS: *Asset tracking, Building information modeling (BIM), Building protocol, Cloud Server, Human resources, Passive radio frequency identification (RFID), Project management, Quality control, Safety, Security, Worker Logistics.*

1. INTRODUCTION

Large scale projects require a productive and efficient workforce to stay on schedule and under budget. Maintaining high efficiency and productivity requires the constant monitoring the work force and project In particular, the status of labor forces is an important area to maintain for completing a project on schedule. A large percentage of construction costs result from the quantity of labor hours spent completing the desired tasks. Thus, by maximizing labor productivity, companies can avoid additional costs due to falling behind schedule. Many factors determine whether workers are able to complete their tasks at the necessary pace including experience, age, skill, motivation, and leadership. Appropriate work conditions can also influence the entire operation, such as project size and complexity, site accessibility, labor availability, equipment use, and local climate (Hendrickson 2009, Lee et al. 2008). In order to determine whether the construction process is operating at maximum efficiency or can be adjusted to improve its effectiveness, additional construction improvements can be identified in terms of productivity analysis of work crews, material transport, and the overall approach to a project. However, the monitoring and analysis of labor productivity has mostly been done manually, in which manual analysis have been shown to be time consuming, subjective to judgments and error prone (Ogelsby 1988, Allmon et al. 2000,

Citation: Costin, A. M., Shaak, A., Teizer, J., Pfeffer, G., Khanzode, A., Saripally, D., Chao, O., Schoner, B. & Shah, S. (2013). Passive RFID-based asset tracking and project management on a large hospital project. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Goodrum et al. 2006). Integrating technology to automate the monitoring and analyses is a way to reduce the human component and increase accuracy and reliability. Projects with higher automation and integration of information technology improved between 31% and 45% in productivity (Zhai et al. 2009).

The University of California San Francisco's (UCSF) Medical Center at Mission Bay is a large, 900 thousand square feet, hospital project that consists of three major buildings, 125 contractors, and roughly 1,200 workers. This public sector project has successfully implemented innovation project delivery models such as Target Value Design, lean construction principles, and Building Information Modeling (BIM). In addition to BIM, the project utilized an RFID-based building access protocol system that provides visibility of personnel and construction assets, including equipment and materials, on the jobsite, and helps the team plan work more efficiently. The use of this technology creates a more intelligent and automated job site, resulting in numerous benefits, such as improved safety and security, equipment protection, improved work quality, and more effective workforce. Importantly, the system allows for the monitoring and verification of protocols and ordinance, such as the San Francisco Office of Economic and Workforce Development (OEWD) mandatory local hiring ordinance (Office of Economic and Workforce Development 2011). The San Francisco OEWD mandates that certain government funded projects hire a percentage of local workers by trade. Although the UCSF hospital does not meet the criteria to follow the ordinance, it is voluntarily doing so to benefit the local community.

This paper highlights the collaboration of the team to apply lean construction principles and BIM within the contractual framework of the project. Additionally, the method of integrating Radio Frequency Identification (RFID) and BIM for real-time tracking of materials, equipment, and personnel is presented.

2. PROBLEM STATEMENT

Large scale projects with a large work force area are expected to contain issues with the sequencing of trades, the safety and security of the site, and quality control. Planning and sequencing of trades throughout this project could potentially be difficult as there will be more than 125 subcontractors, and over 800 workers on the site daily (peak hours will even have close to 1,000 employees on site). Consequently, it is extremely important to be able to monitor all personnel on site at any given time, especially during the interior build-out of the facility, since the trades (e.g. mechanical, electrical, and plumbing) will often be overlapping.

The safety and security of everyone on site, including workers and visitors, is the utmost importance on any jobsite, regardless of size. However, larger and more complex projects can be more challenging to maintain the highest level of safety and security. For instance, in the event of an emergency, an evacuation, or a lock down, being able to determine the exact number of workers and personnel on site will be critical, and the more people there are the bigger the challenge it is to have every single person accounted for. Manual recorded keeping of daily personnel and visitors could be potentially be inadequate, and would require a lot of time. Additionally, the monitoring of a large amount of personnel can be tedious and time consuming. On a traditional construction site, options addressing the challenges associated with safety and security are limited. Before, security would need to be placed at each entrance zone to verify the authorization and monitor the head count of workers entering. Even with personal ID badges, a security guard would have to write down who enters, thus limiting the amount of workers that can enter at a time and slowing down the flow of traffic.

Controlling access to hazardous zones of the jobsite is also important to verify only authorized and trained personnel can gain access. Having an untrained worker enter a hazardous area, such as a high voltage utility room, can lead to serious injury or death. Ensuring workers are properly trained before they are allowed to enter a more stringent building protocol project zone is important. However, it is difficult to monitor who has access to certain zones, even if some workers received proper training. Having a security guard or supervisor at each zone entrance is unfeasible and uneconomical.

Large construction projects also have problems with quality control and rework since there are many trades and workers around in the same area. In such situations, completed tasks by subcontractors are at risk of being damaged due to the amount of traffic through the area or the other subcontractors coming to do other work in the same location. Therefore, minimizing traffic in certain areas and understanding what area a subcontractor needs to be in can help limit rework. However, a supervisor that constantly monitors the workers to verify they do not walk through the wrong areas is not practical.

3. LITERATURE REVIEW

Real-time access to the locations of workers, materials, and equipment has been a significant advancement to the management of construction processes. There have been attempts to automate the analysis and tracking such as mobile tracking in lay down yards. Examples of these attempts include pre-cast concrete, fabricated steel elements, and automated tool tracking. Technology that has been researched to provide real time access include radio frequency identification (RFID) (Jaselskis 1995, Song et al 2006, Ergen et al. 2007, Grau et al. 2009, Costin et al. 2012), ultra wideband (UWB) (Teizer et al. 2007, Cheng et al. 2011, Yang et al. 2011), GPS (Oloufa et al. 2002, Pradhananga and Teizer 2012), and multiple sensors (Razavi and Haas 2010). RFID, UWB, and WLAN technology has been shown to be successful in a variety of applications including asset tracking, inventory management, on-site security upgrades, and productivity analysis (Goodrum et al. 2006, Rueppel and Stuebbe 2008, Li and Becerik-Gerber 2011, Cheng et al. 2011, Taneja et al. 2011). UWB can be implemented to track and determine the location of resources in a jobsite by utilizing multiple readers to identify the location of tags (Bohn and Teizer 2010, Cheng et al. 2011). However, UWB requires a careful installation of multiple readers at known locations and cannot be used when the tags are stationary and the reader is mobile. Additionally, RFID implementation in an outdoor environment led to a 4.2% increment in steel erection productivity (Grau et al. 2009).

3.1 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is a method of communication that uses radio waves. The system is composed of a tag, which is read by an RFID Tag reader, and a computer that receives the data from the reader. The tags can be active (battery powered), semi-passive or semi-active (battery-assisted), or passive (no battery). The transponder and transceiver (reader) gather and transmit the information to a RFID tag wirelessly, without necessarily needing to be in the direct line-of-sigh to the tags. First, the reader sends a radio frequency signal to the tag. The tag then sends the signal back to the reader along with any information or data that it may be storing, such as an identification number as each tag can have its own unique identification number. Upon receiving this data/information, the reader sends it to the computer where it is stored and analysed. The information sent to the computer includes items like the time at which the signal was received, which reader received it, and with what strength. The database in which the information is sent to can be utilized in many ways as the data can be linked to additional information that is stored on the tag. For example, a tag's unique identification number can be linked to further information held in a database that further describes that tag with items like a unit name, trade performed, manufacturer, etc. This information can be made easily accessible to users, such as a project manager, and can utilize queries help to increase productivity and efficiency throughout a project.

RFID technology is rapidly becoming more capable and complex, helping to track materials, workers, and equipment in real time as well as produce a visual of the locations and resources on a construction site. The use of RFID technology has been found to enhance the user's ability to locate materials that have been tracked by the RFID readers with an improvement ratio of 8:1 over manual tracking. The enhancement of this technology has led to testing of passive tags. These tests found that passive ultrahigh frequency (UHF) tags are durable enough to work in various harsh conditions, despite the existence of extreme moisture, pH, temperature, and pressure (Ross et al. 2009). This technology, compared to the limited bar code system that requires line of sight read range, provides significantly greater read-ranges and can be utilized in both outdoor and indoor conditions ranging in temperatures from −40 °C to 200 °C (Ross et al. 2009). Costin and Teizer (2012) also reported that the mobile RFID antenna devices as they are used in many commercial passive RFID applications comply with the Federal Communication Commission (FCC) and Industry Canada RF radiation exposure limits for the general population if a safe distance of humans to the antenna of 20 cm is kept. Though there are many benefits of passive RFID tags, there is a drawback in that there are no self-reporting capabilities. The read range typically is limited to up to ten meters, depending on the antenna type. So though this is significantly greater than a bar code system for example, there are still some limitations. The benefit of having a larger readability range, however, is that a single reader can be utilized to read multiple tags within this range (Costin et al. 2012). This capability is also limited in that environments exposed to either multipath or metal surfaces are at risk of experiencing signal attenuation due to the metal surfaces and the signal bouncing (Vogt and Teizer 2007).

RFID technology has been even further utilized by successfully pairing with Building Information Modelling (BIM) for supply chain management (Sawyer 2008). There are other technologies being researched, but they require the additional resources provided by the facility (Costin et al. 2012). Linking these two technologies will allow for tracking user-specified locations (e.g., at turnstiles or at gates) in real time and lead to more productivity and efficiency on a job site.

3.2 Building Information Modeling (BIM)

Integrated building technologies allow a convergence and integration of systems to play a greater role in overall building performance (Kean 2011). Building Information Modelling (BIM) helps to take the traditional building technologies a step further by adding more dimensions to the current 3D models. BIM pairs the geometric and parametric properties of a building's 3D model with all the information and properties of the building, such as information on the products, the site schedule sequencing, and owner histories (Eastman et al. 2008). With this technology, each component of the model can be viewed as well as its relationship with other objects in the model and the logical classification of objects in the model. All of this information is actually stored within the model. This is a very promising advancement in the Architecture, Engineering and Construction (AEC) industry as it creates an accurate, virtual digital model of a project (Eastman et al. 2008). BIM integrates all aspects of a project such as the structural, architectural, mechanical, electrical, plumbing (MEP), energy, etc. into the same platform, helping to lead to a better design through collaboration as well as optimizing performance. These benefits have led to a dramatic increase of the use of BIM over the years, in which 71% of construction companies, 70% of architects, and 74% of contractors are using BIM, and the use is expected to keep increasing (McGraw-Hill 2012).

Since this technology allows objects to hold their properties and are capable of parametric modeling, many manual techniques of tasks like estimating and scheduling have been replaced. BIM creates a platform that allows real time estimation and scheduling to occur based on the 3D model of the project created, both in the construction and operation phase. This changes the way a project has traditionally been categorized and how tasks are divided. The program has developed into a strong tool for project design and construction processes as it is continually receiving efforts to enhance its functionality and capabilities. Pragmatically speaking, BIM is a great tool as it looks at the whole project cycle, including the future of the project when it's in the operation phase. This is crucial as the design and construction phases of a project only constitute a small portion of the time and money that goes into the life cycle of a project. BIM helps to plan and estimate what the operation phase of the project will be like, and uses this throughout the design and construction phase.

4. EXPERIMENTAL ENGINEERING DESIGN

The purpose of this research is to utilize RFID-BIM integration to generate real-time data to produce leading indicators for safety and building protocol control. Additionally, the executed approach is to optimize cost and schedule while maintaining the scope, quality and performance. One of the many goals of the innovative project delivery models implemented on this site is to enhance quality control by reducing rework or damage of finished work.

The UCSF Medical Center team partnered with ThingMagic, Trimble's Radio-Frequency Identification (RFID) Division, and Georgia Tech in order to implement RFID-based tracking devices on the project and analyze the gathered data. These devices are a proposed solution to the sequencing, safety, security, and quality challenges previously mentioned. The RFID based building access will ensure more visibility and tracking of the equipment, materials, and personnel entering and exiting the jobsite while also allowing for the project team to increase work planning efficiency. RFID technology will present measures and data to help prevent these issues. The data analysis will allow for more efficient planning and work flow. This method of planning will help limit the amount of rework performed and limit access to zones where work has been completed, helping to limit damage. The entry security as well as asset and personnel tracking will help enhance the safety of the job site.

Approximately 80 RFID tag readers were installed in the infrastructure of the new building and multiple secure turnstiles with tag readers were places at the access points. The site was designated into different zones, each with a protocol level. The protocol level was based on the safety and security requirements, and authorized workers need specific training for each level to enter. All workers and visitors on site are issued a passive UHF-RFID-enabled identification badge to be read as the individual passes through the turnstiles or walks within the range of other sensors (see Figure 1).

There are two data types: the real-time data and stored data. The real-time data reports the current location when a tag is read, such as when an alert is sent for an unauthorized worker. All the real-time data is then reported to a cloud-based web portal where real-time email notifications and reports can be delivered daily. In addition to this reporting, a web service has been created in order to provide external software clients access to the data. This is done so the data can be analyzed and visualized in 3D. For example, Tekla BIM software with a custom plug-in will allow the users to filter the data to zoom in on the relevant data of the building section, time span, people, or assets desired (see Figure 2). Managers can now monitor the flow of people in and out of different zones, allowing for an instant email alert to be sent when an employee enters an unauthorized zone. These real time updates will be crucial in the event of an emergency as it will provide authorities will be able to determine who has been left in the building and where.

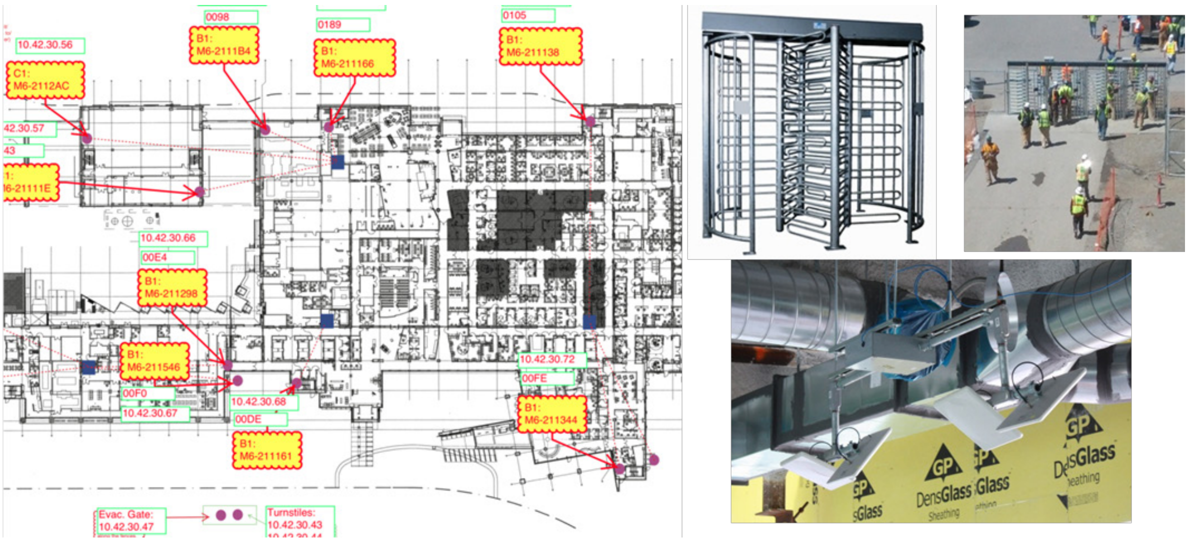


Fig. 1: Map of zones, turn-style readers, site entrance and fixed passive RFID reader and antennas.

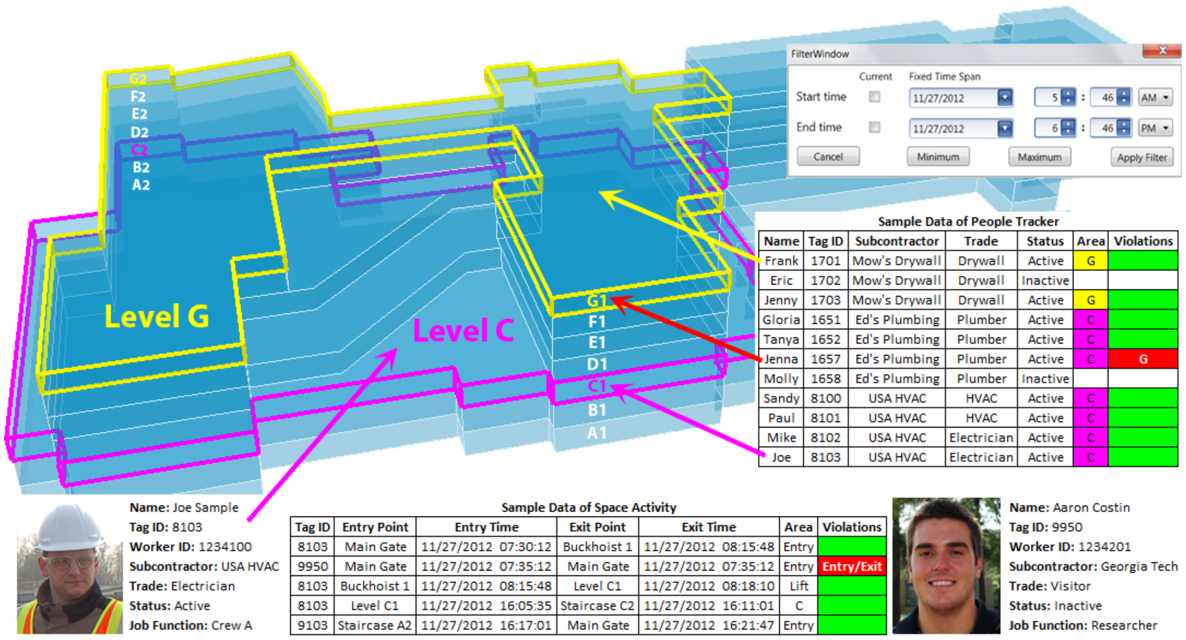


Fig. 2: Georgia Tech's software plug-in with workers and sample data of workers' locations in a BIM model.

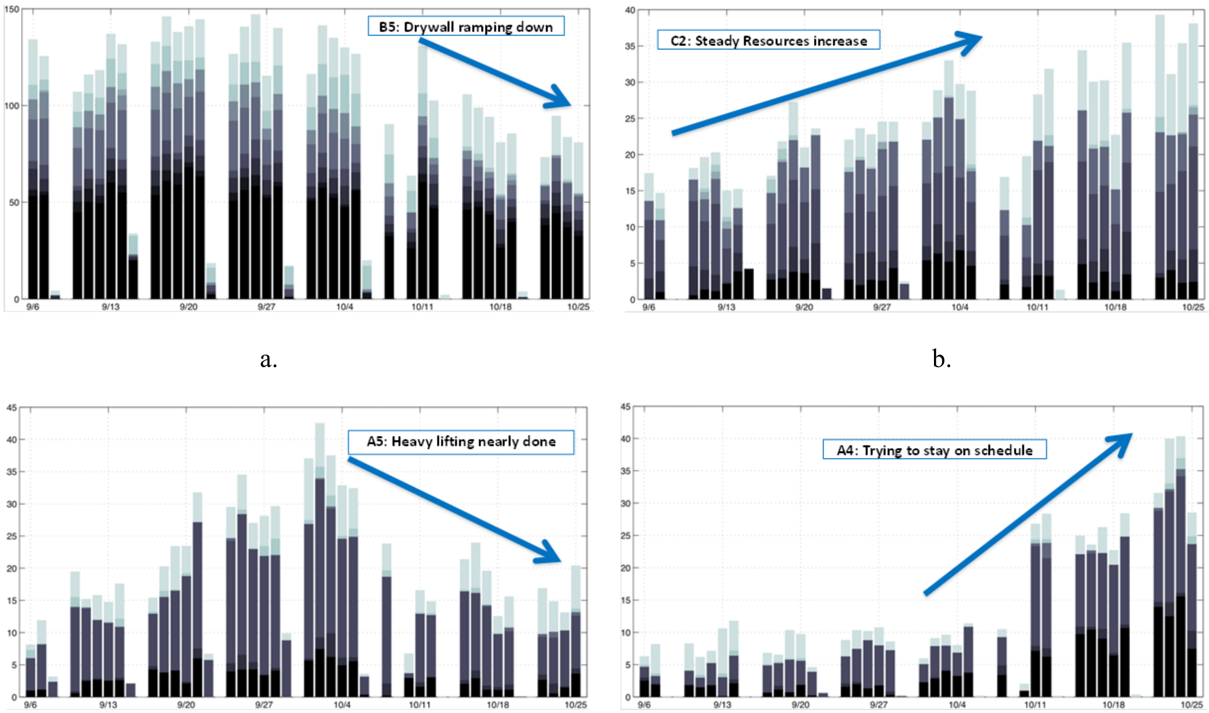
The modeling began at 25% design phase, thus ensuring that subcontractors were able to report their constructability inputs into the permit drawings. Superintendents also worked with the modelers in order to create a model that accurately portrays the means and methods of the planned construction as well as provide the details specific to the project conditions that may become part of the permit documents. This collaboration ensures that the project is in compliance with all the necessary permit documents and requirements. The structural models created are directly used to create the fabrication and installation drawings. By doing this, it will guarantee that everything installed meets the design requirements while satisfying the required permitting documents. The design models will also feed into Total Station units for an accurate site layout and installation. Many benefits come from creating a highly detailed model, such as the validation of the design, user requirements, and constructability as well as benefits in cost-savings, more reliable scheduling and increased field productivity. The time and effort put into creating these highly coordinated models results in higher predictability for schedule, material, and labor, leading to cost savings for the owners as the contingency budget can be lowered. These models allow for the modeling of detailed architectural, structural, and MEPF systems, including hangers and seismic bracing, drywall framing, concrete, rebar, exterior skin and site utilities. The detail can go as far to show drywall models including “critical” framing, such as corners, doors, and MEP opening framing, as well as the infill framing for crowded rooms such as patient rooms, ICUs, and operating rooms.

5. OPERATING RESULTS

In addition to the real time data the system produced, the stored data was filtered and analyzed for various aspects. The data can be graphed to compare the work in the different zones. Activities such as productivity, number of workers, and scheduling can be visualized to see the trends, progress, or even compare whether the work is on schedule. Having the data in visual form is important to for planning and coordinating future work. Importantly, knowing the current status and productivity rate allows for a more accurate assessment of what is needed. For instance, Figures 3a and 3b show the work is becoming to completion, and therefore not many workers are needed. Also, Figures 3b and 3c show the increase in number of workers to maintain the current schedule.

Verifying the compliance to local, state, or federal regulations is another important feature this system provides. For example, The San Francisco OEWD mandates that certain government funded projects hire a percentage of local workers by trade. Although the UCSF hospital does not meet the criteria to follow the ordinance, it is voluntarily doing so to benefit the local community. The goal is to have a mandatory participation level of 25% of all project hours within each trade to be performed by local residents. Each employee’s information, including their trade and zip code, will be placed in a data base that is linked to their identification number. This new RFID technology will be able to track all employees by their given identification number, thus providing the resources to obtain an accurate assessment of the amount of employees with the local residential zip code. With this information, USCF has been able to accurately report the number of local residents on the site and the amount of hours they have performed in their trade. As seen in Figure 4, the UCSF Medical Center successfully met their goal to reach 25% local resident employees, and is working on achieving a 35% rate in 2014.

The system records all safety and security violations, which is important for record keeping and the production of leading indicators for safety and building protocols. When a worker enters an unauthorized zone, an alert is sent to the project manager notifying him of the breach. In addition, each breach is kept in a log, which can then be analyzed to fix the problem. For instance, if an unauthorized worker enters in by mistake, he will learn to not go in there without proper training. Additionally, a log will notify what workers still need to be trained to enter that zone. Examples of the log of violations for a specific area and duration are shown in Figure 2 as well. These violations were created by a visitor and a worker. It is important they had special authorization to enter the zone.



a. b.

c. d.

Fig. 3: Full-time equivalent workers per day per contractor for work areas (a) B5, (b) C2, (c) A5, and (d) A4.

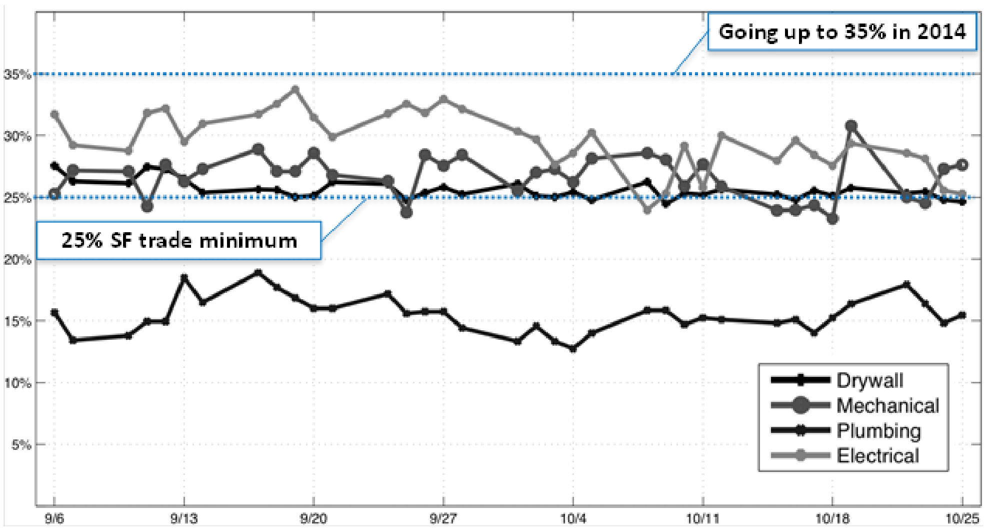


Fig. 4: Percentage of San Fransisco-based workers by subcontractor (Monday through Friday).

6. DISCUSSION AND CONCLUSIONS

RFID tracking technology applied on construction assets creates a more systematic, automated, and intelligent job site and results in benefits to both the project team and the UCSF Medical Center. The developed hardware system and data mining algorithms are able to detect personnel and assets as far as three to five meters away from the reader antenna, which is unlike the current, conventional manual access control. With this kind of range, workers will no longer have to swipe a badge at each sensor as they will be able to simply pass through check points and portals. Long range readers reduce the numbers of readers need to be installed, which is important on a large, congested site such as a hospital.

The following benefits and limitations were identified

6.1 Improved Security

Providing an accurate headcount has made it easier to ensure the safety of everyone, which is important on this large, newly developed, urban site that the hospital is being developed on. Crews are now easier to find and convey important messages to. Being able to locate the crews could be the difference in life or death in an emergency situation. The new technology allows for the assurance that only badged, authorized employees are entering the site and the zones that they are authorized for, which increases safety and lowers risks in those zones that may contain expensive equipment and materials. No longer will there need to be a hired security guard or supervisor just to monitor the work force in the various sections of the building. The use of this technology eliminates the need for these personnel and thus lowers costs.

6.2 Equipment Protection

Since this is a state of the art facility being constructed, there is a significant amount of expensive medical equipment to be installed. The new RFID system allows for all assets and equipment to be securely tracked and located at all times. This prevents the equipment from being lost or missing, which could potentially be a negative impact on the project's cost and schedule.

6.3 Improved Quality

Rework and damage to completed work are very realistic threats to the quality of the project. Foot traffic over completed work can cause damage to these finished projects and without proper monitoring and planning, rework is possible. Minimizing this traffic and ensuring that subcontractors are only in locations where they are necessary will help to limit damage and rework. A way to do this is to control and monitor access to the site and to ensure that workers are properly trained before they can enter the different project zones. With RFID technology, the project team is able to do this and is better able to monitor the progress of the different work zones, helping to better protect the finished work.

6.4 More Effective Workforce

As labor is almost half of a project's construction cost, it is imperative to improve the worker logistics on a job site. The RFID technology helps make this happen. With the data presented by the new technology, subcontractors are able to more efficiently plan their work, helping to meet project needs and identify variances. The data provides an understanding of how many workers are present on site daily and where majority of the work is being performed. This helps the subcontractors determine the appropriate amount of workers to deploy, preventing over- or under- staffing the project. The owner's dollars are being efficiently spent when the right people and skill sets are in the right place at the right time, and this comes from the improved work flow created. The real time data analysis during each work day is drastically different and more efficient than in the past when construction managers and owners used to have to wait for weeks or months to get the data analysis of how efficiently the workforce is performing, thus wasting money. The new system also provides the ability to measure travel times between work zones, with this information an adjustment can be made in material placement or path of travel, thus enhancing productive worker time.

6.5 Cultural Factors

Initially, subcontractors and workers showed concern that the system monitored their exact location at all times, however, through seminars and training, it was conveyed that the purpose of the system is to identify the zones where the worker was last seen, not determine their exact location at all times. Communicating this to the workers allowed them to feel more comfortable and see the benefits of the RFID system. Benefits such as enhancing the security of the project, only allowing authorized personnel onto the site, or ensuring that individuals without the proper training do not enter the wrong zones gave the workers a higher sense of security and assured the subcontractors that costly errors can be avoided.

6.6 Current Limitations

Although the benefits seem to outweigh its limitations, some warrant further investigation, for example: in building construction dynamically changing floor may require RFID hardware to be frequently relocated, few data mining algorithms exist that currently take not full advantage of the data that is gathered, people issues such as the perception of being tracked, legal issues of who owns the data and for what purposes it is used.

7. REFERENCES

Allmon, E., Haas, C.T., Borcherding, J.D., Goodrum, P.M. (2000). U.S. construction labor productivity trends, 1970–1998, *ASCE Journal of Construction Engineering and Management*, 126 (2) 97–104.

Cheng, T., Venugopal, M., Teizer, J., and Vela, P.A. (2011). Performance Evaluation of Ultra Wideband Technology for Construction Resource Location Tracking in Harsh Environments, *Automation in Construction*, Elsevier, 20(8), 1173-1184.

Costin, A., Pradhanang, N., and Teizer, J. (2012). Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project, *Automation in Construction*, 24, 1-15.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K., (2008). *BIM Handbook – A Guide to Building Information Modeling*. John Wiley & Sons, Inc., N.J.

Ergen, E., Akinci, B., and Sacks, R. (2007). Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. *Automation in Construction*, 16(3), 354-367.

Goodrum, P., McLaren, M., Durfee, A. (2006). The application of active radio frequency identification technology for tool tracking on construction job sites. *Automation in Construction*. 15 292–302

Grau, D., Caldas, C.H., Haas, C.T., Goodrum, P.M., Gong, J. (2009). Assessing the impact of materials tracking technologies on construction craft productivity. *Automation in Construction*. 18, 903–911.

Grau, D., Zengb, L., and Xiaob, Y. (2012). Automatically tracking engineered components through shipping and receiving processes with passive identification technologies, *Automation in Construction*, Elsevier, 28, 36-44.

Hendrickson, C. (2008). Project Management for Construction. http://pmbook.ce.cmu.edu (January 27, 2009).

Jaselskis, E.J. (1995). Radiofrequency Identification Applications in Construction-Industry. *Journal of Construction Engineering and Management*, 121(2), 189-196.

Jaselskis, E. J. and El-Misalami, T. (2003). Implementing radio frequency identification in the construction process. *Journal of Construction Engineering and Management*, 129(6) 680-688.

Kean, T. (2011). “Current Trends and Future Outlook Examining the IFMA industry trend report.” *Military Engineer*, 103(673), 67-68.

Li, N. and Becerik-Gerber, B. (2011). Performance-based evaluation of RFID-based indoor location sensing solutions for the built environment. *Advanced Engineering Informatics*, 25(3), 535-546.

Lee, J.B., et al., (2008). A feasibility study on optimal lifting planning in the high-rise apartment building construction. *Journal of Korea Institute of Construction Engineering and Management*. 9, 185–193.

McGraw-Hill (2012). SmartMarket Report: The Business Value of BIM in North America Multi-Year Trend Analysis and User Ratings (2007–2012) Construction. *McGraw-Hill Construction*.

Office of Economic and Workforce Development. “Local Hire.” WorkforceDevelopmentSF. http://www.workforcedevelopmentsf.org/aboutus/index.php?option=com_content&view=article&id=88&Itemid =102, 2011, (Accessed January 13, 2012).

Oglesby, C. (1988). Productivity improvement in construction. *Construction Engineering and Project Management*. 146–271.

Oloufa, A.A., Ikeda, M., and Oda, H. (2002). GPS Based Wireless Collision Detection of Construction Equipment, Proceedings of 19th ISARC, National Institute of Standards and Technology, Gaithersburg, Maryland. September 23-25, 461-466.

Pradhananga, N. and Teizer, J. (2013). Automatic Spatio-Temporal Analysis of Construction Equipment Operations using GPS Data, *Automation in Construction*, Elsevier, 29, 107-122.

Razavi, S.N., Haas, C.T. (2010). Multisensor data fusion for on-site materials tracking in Construction, *Automation in Construction*. 19, 1037–1046.

Ross, W.A., Burns, S.E., Wu, P.Y., Jared, D.M. (2009). Radio frequency identification tracking technology applied to testing of transportation construction materials. *Journal of the Transportation Research Board*, 3–12.

Rüppel, U., and Stübbe, K.. (2008). BIM Based Indoor-Emergency-Navigation-System for Complex Buildings. In: *Tsinghua Science and Technology Journal*, Tsinghua University, 13(S1), 362-367.

Sawyer, T. (2008). $1-Billion Jigsaw Puzzle Has Builder Modeling Supply Chains." http://enr.construction.com/features/technologyEconst/archives/080423-1.asp.

Song, J, Haas, C.T., and Caldas, C.H. (2006). Tracking the location of materials on construction job sites, *Journal of Construction Engineering and Management*, 132(9), 911-918.

Taneja, S., Akcamete, A., Akinci, B., Garrett, J.H., Soibelman, L., East, W.E. (2011). Analysis of Three Indoor Localization Technologies for Supporting Operations and Maintenance Field Tasks, *Computing in Civil Engineering*, 26, p. 708-719.

Vogt, B. and Teizer, J. (2007).Sparse laser scanning to improve off-shore pipe-fitting productivity. *Proceedings of the Construction Research Congress*. Freeport, Bahamas, May 6–8, 2007,

Xie, H., Shi, W. and Issa, R. R. A. (2010). Implementation of BIM/RFID in computer-aided design-manufacturing-installation process. Computer Science and Information Technology (ICCSIT), *3rd IEEE International Conference*, 2, p. 107.

Yang, J., Cheng, T., Teizer, J., Vela, P.A., Shi, Z.K. (2011). A performance evaluation of vision and radio frequency tracking methods for interacting workforce. *Advanced Engineering Informatics*. Elsevier, 25 (4), 736–747.

Zhai, D., Goodrum, P.M., Haas, C.T., Caldas, C.H. (2009). Relationship between the automation and integration of construction information systems and productivity. *J. Construction Engineering Management*. 135 (8), 746–753.

REAL-TIME TABLET-BASED VIRTUAL REALITY IMPLEMENTATION TO FACILITATE TUNNEL BORING MACHINE STEERING CONTROL IN TUNNEL CONSTRUCTION

Sheng Mao, Xuesong Shen, Ming Lu, & Xiaodong Wu
Department of Civil and Environmental Engineering, University of Alberta, Canada

ABSTRACT: *On the majority of tunneling projects, steering a tunnel boring machine (TBM) currently relies on a laser station which projects a laser beam onto a laser target board mounted on the TBM. However, laser target boards lack accuracy and reliability, thus potentially contributing to quality defects and increased risks of schedule delay and budget overrun in tunnel construction. This research has developed a cost-effective, real-time solution called "virtual laser target board (VLTB)" to substitute for physical laser target boards in guiding TBM during construction. Through integrating automation control mechanisms, innovative computing algorithms, and wireless network technologies, the VLTB technology transforms a popular survey tool, the robotic total station, into a construction control robot which precisely tracks and positions the TBM. By applying an enhanced point-to-angle computing algorithm, VLTB calculates the exact coordinates of the cutter head center on the working TBM in millimeter-level accuracy. The invisible cutter head center is projected onto a "virtual laser target board" on a tablet interface in relation to the as-designed alignment. Based on field testing, VLTB is found to be able to lend real-time, relevant assistance to TBM operators and tunnel surveyors. Compared to other advanced technologies in the market, VLTB provides a simpler and more flexible solution to ensure tunnel alignment control and enhance quality and productivity performances in tunnel construction.*

KEYWORDS: *Tunnel Construction, Tunnel Boring Machine, Virtual Reality, Mobile Computing, Machine Control and Guidance, Robotic Total Station.*

1. INTRODUCTION

In tunnel construction, the operator steers the tunnel boring machine (TBM) from the launching shaft to the receiving shaft. The steering control is a challenging process, as the operator can barely utilize any references as landmarks to drive the TBM along the designed path. In reality, the operator and the surveyors fully cooperate and follow a specific protocol. The surveyors are responsible for setting up a series of geospatial benchmarks from the entrance shaft to the point near the working TBM, while the operator will guide the TBM following a laser beam the alignment of which is consistent with the design and is calibrated based on surveyors' benchmarks. In the current practice, the surveyors establish a laser beam parallel to the tunnel alignment; the laser leaves a footprint on a laser target board mounted on the TBM. When the TBM is on the designed path, the laser dot is supposed to fall on the center of the target board. Thus, the operator merely follows the laser footprint in advancing TBM.

Nonetheless, this process is not as reliable or accurate as desired. Steering TBM by following the laser footprint is analogous to hiking in a forest by following the sun. There are several factors affecting the outcome. First, the information available for the operator is scarce. The operator barely knows where the TBM is headed, nor the exact position of the TBM in the tunnel. The operator has to imagine the TBM position and attitude in the tunnel and made decisions based on guts feelings. Second, the reliability of the system cannot be verified on demand. The accuracy of guidance is decided by the parallelism of the laser beam to the tunnel alignment, and in practice, the parallelism is difficult to be verified. Slight displacement of the laser will result in a magnified deviation on the laser target board, causing TBM to stray beyond the error tolerances. After all, the process heavily depends on interpretation and verification by surveyors. The surveyors need to interpret TBM's rough position and attitude by counting the quantity of concrete blocks already installed and checking inclinometers on the TBM. They also need to interrupt the construction and verify the parallelism of the laser regularly. Moreover, as it is error prone and time consuming to relocate and calibrate the laser, surveyors intend to reduce the frequency of moving the laser station. However, advancing the TBM further away from the laser source yields even lower precision in laser projection; as the distance grows, a trivial mistake to the laser will lead to a much more significant error in TBM guidance control.

Citation: Mao, S., Shen, X., Lu, M. & Wu, X. (2013). Real-time tablet-based virtual reality implementation to facilitate tunnel boring machine steering control in tunnel construction. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

As such, TBM needs to be shut down more frequently to allow surveyors to check or move the laser system, severely undermining the productivity of tunnel construction.

In short, the operator needs to visualize the status of the TBM in relation to the as-designed tunnel alignment in real time; however, the laser system is not effective or reliable to provide the critical guidance as desired. In this paper, we describe an innovative system resulting from recent research, which integrates automated surveying, communication, and visualization in order to lend decision support to both tunnel surveyors and TBM operators. In addition, the data will be recorded in real time and analytical results transferred via wireless networks from the tunnel to the above ground office. The core idea of the method is to survey the TBM status in real time and visualize the most relevant information on a virtual laser target board, thus helping the operator and surveyor to make sound decisions as tunneling operations continuously unfold.

Shen and Lu (2012) thoroughly evaluated current laser guidance methods, and categorized the tunnel guidance solutions into passive and active groups. The classic laser system as described above is a passive laser system, and the laser is maintained parallel to the tunnel alignment and points at a laser target board. The laser can only show the deviation of the TBM from the alignment, while rolling and pitching angles are determined by inclinometers installed on TBM. Note the critical yawing angle is not detectable in the commonly available laser system. In a modified version, the target board is replaced by two special target boards, with the front board being transparent. As such, laser will leave footprints on both boards and the yawing direction can be computed from the horizontal deviations of the two laser footprints (Shen and Lu, 2012).

The yawing angle is very critical and irreplaceable for the operator to control where the TBM is headed (turning right or left). Active laser systems focus on how to improve the passive laser systems and try to measure yawing and pitching angles automatically (Shen and Lu, 2012). The two popular commercial solutions are from tacs GmbH (tacs GmbH, 2004) and VMT GmbH (VMT GmbH, 2003). Both enhance the dual-target-board design. In tacs GmbH system, the positions of laser footprints are first captured by digital cameras, then deviations of footprints are determined by image processing software (Shen and Lu, 2012; tacs GmbH, n.d.). In contrast, VMT GmbH turns the front and back target boards into light-sensitive devices. In a similar way, the deviations of the laser footprints are measured directly on the boards, and then the processing software calculates the path of the laser (Shen and Lu, 2012).

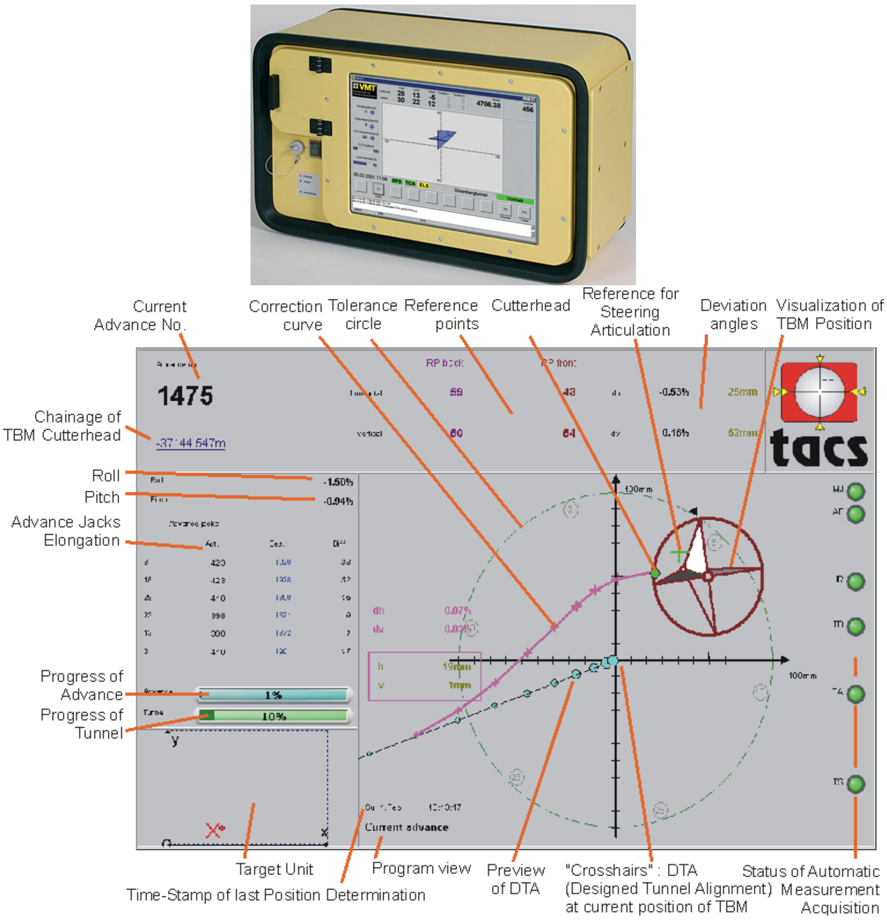


Fig. 1: Software interfaces from VMT GmbH (up) (courtesy of VMT GmbH, 2003) and tacs GmbH (down) (courtesy of Tacs GmbH, n.d.)

Both passive and active laser target boards provide the basis to further develop methods for visualizing TBM deviations, designed to assist the operator in steering the TBM. Liang and Lu (2010) developed a three-dimensional visualization system for the TBM, which can visualize the attitude of the TBM as well as the relative location between the TBM and existing pipelines. In particular, the system provides an intuitive view of heading control jacks of the TBM (Liang and Lu, 2010). The real time 3D visualization system is complicated in terms of design and implementation and demands substantial computing resources. Thus, the present research turns to a straightforward, intuitive, and robust system design as desired by the operator and the surveyor in making real time decisions during the tunneling process. And to our best knowledge, no existing commercial solution is as elegant or capable yet.

2. SYSTEM ARCHITECTURE

2.1 Tunnel Alignment and Deviations

A tunnel is designed to follow a path in the underground space at a given depth. During construction, the surveyors will figure out the path as per the design and project the guidance on the laser target board in order to guide the operator of the tunnel boring machine. Inside the tunnel, the path is always defined as *tunnel alignment*, which passes through the centers of all the cross sections of the tunnel. For a straight tunnel, the alignment is simply defined as an arrow pointing from the start point to the end point, while occasionally, for a tunnel consisting of straight sections and curved sections, the alignment is much more complex.

While advancing the TBM, the operator ensures the actual path taken by the TBM center overlaps with the tunnel alignment as close as possible. When the TBM strays from the tunnel alignment, deviations between the expected center position and the actual position yield. The deviations are characterized by two components: the line deviation is the horizontal offset from the online position, and the level or grade deviation is the vertical offset. As shown in Fig. 2, the line and grade deviations are defined as horizontal and vertical displacement between Y axis of TBM body and the tunnel alignment.

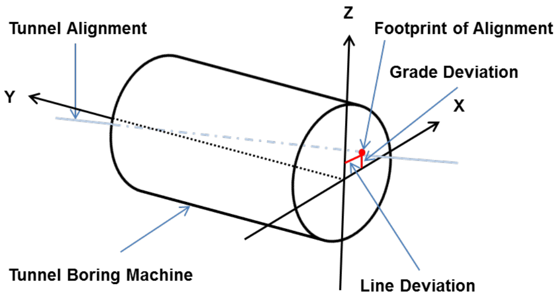


Fig. 2: Deviations of TBM

The operator is responsible for ensuring the deviation falls within a given tolerance, and the tolerance is chosen based on many factors. For example, the drainage tunnel is less tolerant (more stringent) than the traffic tunnel in terms of tunnel alignment control, as in a drainage tunnel the direction and speed of the storm water flow is affected by the tunnel alignment. Any “out of bounds” deviations may eventually affect the normal functionality of the tunnel.

After fixing the tunnel alignment, the surveyors need to define the corresponding laser path, which will be projected onto the laser target board installed on the TBM. However, the tunnel alignment is not always visible during the tunnel construction, as workers and equipment can easily occupy the space inside the tunnel and block the laser projection. Note the TBM is equipped with a gantry system at its backend, carrying supporting systems such as transformers, ventilation systems, conveyors and muck carts. The gantry system takes substantial space, making it impossible to project laser along the tunnel alignment. Therefore, the visible surveying and guidance window inside the tunnel is very narrow and often limited to a corner instead of the center of the tunnel cross-section.

2.2 Virtual Laser Target Board System

2.2.1 Design Overview

The VLTB system runs on an enhanced version of point-to-angle computing algorithm originally proposed by Shen and Lu (2012). The algorithm requires three prisms, which can be located anywhere in a solid object such as in a limited survey window near the top right corner of TBM. Despite the increased computational complexity, the real-time computing performance of the enhanced algorithm in terms of accuracy and response time has been maintained. By pre-registering the relative positions of the cutter head and three selected targets at rear end of TBM, the absolute center of the cutter head can be determined with the accuracy in the order of 1-2 millimeters based on real time TBM positioning. A vector linking two points in the underground space, namely the center of the cutter head and the center of the rear section of the TBM are projected on a virtual laser target board in order to visualize the TBM position and attitude. All the components in the system are connected through wireless networks. Both the operator at the frontend and the site foreman above ground are kept current of the tunnel as-built alignment and the actual construction progress in real-time.

2.2.2 Architecture

The virtual laser target board system is divided into three subsystems by functionality: the surveying subsystem, the communication subsystem and the control subsystem. As previously stated, the surveying subsystem comprises of target prisms and a robotic total station. The robotic total station is a total station enhanced with robotic control mechanisms and application programming interfaces (API). Users can control the robotic total station through the API and perform automation tasks such as target searching, tracking and surveying. In the surveying subsystem, the robotic total station locks the coordinates of the prisms by a pre-scheduled plan or on request from the control subsystem. The survey data are sent via the communication subsystem to inform the control subsystem.

As shown in Fig. 3, the system is connected by the communication subsystem (ZigBee wireless network). Operator sends survey commands and receives surveyed results through tablet-based interfaces of the control subsystem (a tablet computer). Note the guidance information is also shown on the tablet. On the other hand, the surveying subsystem (total station) receives survey commands, reads target prisms and broadcasts surveyed results via the ZigBee network. Above the tunnel, site server captures broadcasted results, and submits the changes to the database, which notifies 3D visualization programs to re-render the time-dependent 3D models.

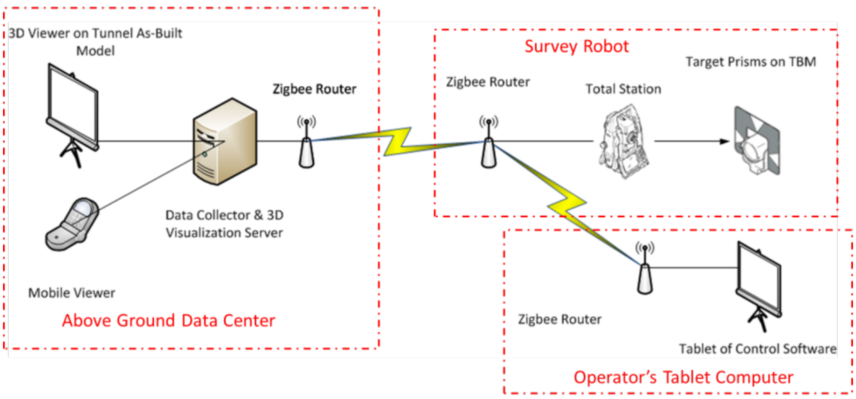


Fig. 3: System components and architecture

The communication subsystem is responsible for data communication, making the underlying data available to the user and the other subsystems. In different scenarios, the communication subsystem is configured differently, for example, for long-distance communication, ZigBee technology can be used, while for short-distance or low-latency scenario, Bluetooth technology can be employed instead. But for the other modules, the communication subsystem acts like a black box, and handles input/out data using standard input/output protocols. In tunnel construction, the survey premise will gradually move deeper in the tunnel with the advance of the TBM. As such, the distance between the data source and the above-ground data receiver continuously increases. As the mount of the robotic total station is relocated once every 200 m, the distance between the operator's tablet computer and the robotic total station gradually increases up to 200 m. In consideration of these constraints, a communication technology such as ZigBee that supports relay transmission is preferable.

The control subsystem handles user interaction, survey control, data persistence and failure recovery. It interacts with both surveyors and operators. For instance, surveyors can set up the coordinates of robotic total stations and target prisms through the system configuration interface; on the same interface, they can also check alignment deviations and schedule automatic surveys. For operators, they interact directly with the virtual laser target board (VLTB) interface and read the current steering guidance information. It is noteworthy the VLTB system installation is simple and doesn't require special laser receivers like those used in VMT and tacs systems; the system is a collection of inexpensive components or mature, off-the-shelf technologies.

The software architecture of VLTB comprises of four different sub modules, and in the current version of the software system, all the four modules are implemented in the control subsystem (Shen and Lu, 2012). The four sub modules are:

- Total station control
- Data serialization and logging
- Data processing
- Data Visualization

As the communication subsystem is treated as a black box, all messages are broadcasted over the ZigBee-based wireless sensor network. The total station control module interprets the robotic total station control protocol, and the total station operates itself and controlled by commands issued from manufacturer-defined APIs. The data serialization and logging sub module preserves all incoming and outgoing broadcast messages, and keeps track of all the events for further integrity check and debug purposes. The data processing module is the core, which applies innovative algorithms to process surveyed data and produces results for support decision processes by surveyors and operators. The data visualization utilizes produced results and renders them in a more intuitive, role specific way in support of decision making and project control.

2.2.3 User Interface

There are two control panels in the VLTB system, one is for the operator and the other is for the surveyor. As shown in Fig. 4, the interface on the left is used by the surveyor and the interface on the right is used by the TBM operator. The surveyor can set up the total station, connect to the database, add or remove target/reference prisms and perform surveying through the interface. Meanwhile, the operator only needs to know the deviations of rear/head of TBM, and also the attitudes of the TBM. The information is neatly presented and the system runs automatically and maintenance-free.

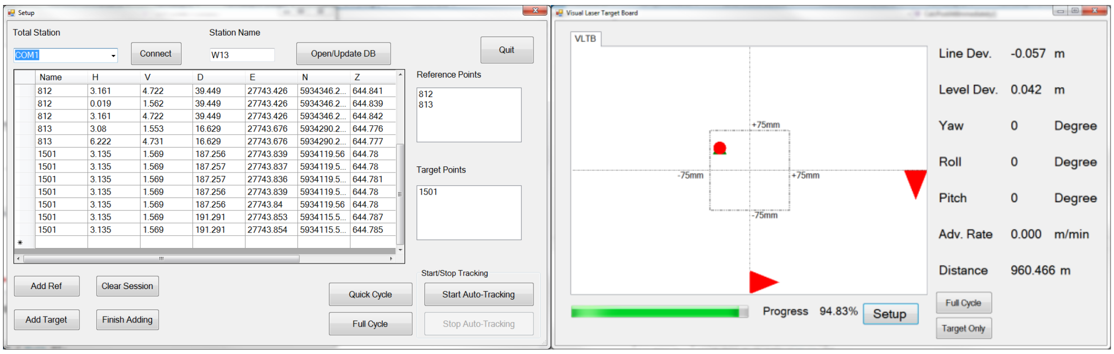


Fig. 4: User Interface of the VLTB: Surveyor Version (Left) and Operator Version (Right)

Left image in Fig. 4 is the surveyor's interface. It allows surveyors to add and remove reference and target points, survey the TBM, and perform system self-check. Each target is given a unique name and stored with its metadata (the horizontal/vertical angle and slope distance) and its coordinates (coordinates on East, North, Zenith directions). A software session is used to preserve surveyors' setup when re-launching the interface; previously set data will be automatically loaded. Every time the surveyors relocate the robotic total station, they need to recreate a session to preserve the working environment.

The operator's interface is shown in the right image of Fig. 4. The two-dimensional diagram shows guidance information for the operator. In the diagram, the tunnel alignment passes through the center of cross, and is perpendicular to the observation plane (tunnel cross section). A red circle and a green triangle represent the rear end and the cutter head of TBM, respectively, while the vector connecting the two points represents the body axis of TBM. When the body axis of TBM is not along the tunnel alignment, the circle and triangle move away from each other. When the TBM stray away from the alignment, the circle and triangle move away from the center of cross in real time. The steering guidance is neatly simplified as a process to keep the circle and triangle within the square boundary and shorten the length of the body vector as much as possible. Moreover, the red triangle arrows suggest the direction of the next maneuvers for the TBM operator (turning right and downward as in Fig. 4), assisting operators in making decisions on steering control. The numbers on the right side of the interface show line/level deviations, yaw/roll/pitch angles, advancing speed of TBM and chainage distance of the TBM. Displaying such real time information is useful to keep track of the current TBM position status and the construction progress. Comparing related interfaces of commercial solutions (such as VMT and tacs), the VLTB interface simplifies the information shown to TBM operators and helps operators understand the status and make crucial decisions in an intuitive and straightforward manner.

2.2.4 Robustness Design

The underground construction environment is complicated, the space is confined, and the humidity is high. All these factors negatively affect the robustness and reliability of the tunnel guidance system. Consequently, the tunnel construction projects are vulnerable to system failures: A single failure may cause a huge impact on the progress and quality of construction, as the TBM cannot advance even an inch without reliable guidance

The five most critical bottlenecks of the VLTB system design are geometry of surveying, battery life, software logic, communication quality, and device deployment. The robotic total station is tasked to survey targets on the TBM along with two reference points with known coordinates on the tunnel wall. One of the concerns is the dispersion of the laser. As the tunnel advances away from the robotic total station, the laser footprint grows larger. If the two prisms are too close to each other, the total station can be confused and the measurements by the total station may be invalid. In tracking a smaller diameter TBM, it is very difficult to install the three prisms at positions on the TBM which are sufficiently apart from one another while falling in the narrow field of vision of the total station; therefore, the processing program will automatically choose corresponding algorithms based on how many target prisms are “surveyable”, as shown in Fig. 5. Generally at least three surveyable prisms on the TBM allow the determination of exact 3D positioning of the TBM in the underground space; while one surveyable prism only yields the deviations of the end section of the TBM. Moreover, to obtain high accuracy results, the ideal geometric layout of prisms should be such that all the prisms fall in one plane perpendicular to the tunnel alignment (or the laser projection). In addition, the system is capable to perform automatic self-check, report any possible displacement, and carry out self-calibration operations of the total station as soon as possible.

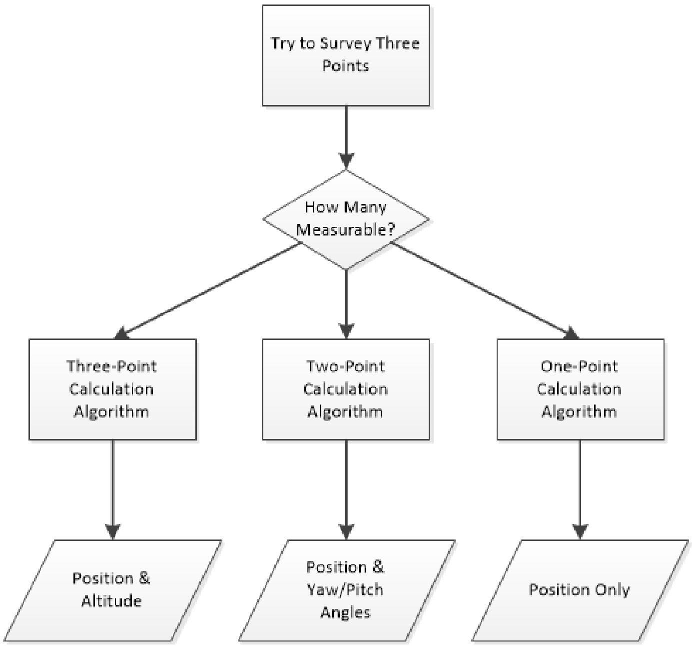


Fig. 5: System will automatically choose processing algorithm based on number of measurable targets.

The second problem is the battery management. The robotic total station, the tablet computer, and the wireless sensor network are all powered by batteries; any power failure is fatal to the entire system. Currently, several manufacturers of robotic total stations provide special external battery packs which can support the total station to continuously operate for over eight hours. Also, the tablet computer can be supported by the power supply inside the tunnel besides the TBM control panel. The Universal Serial Bus (USB) ZigBee nodes are powered through the USB interface of a laptop computer, and the standalone ZigBee nodes use external batteries as the energy source.

The third robustness problem is software logic. The software system uses both error codes and exceptions to protect the system integrity (Miller and Tripathi, 1997). The error codes are embedded in local logic and they represent known issues with the system. When the system receives error codes, it immediately triggers predefined actions, for example “waiting for next survey”. As for exceptions, they represent events that are not clearly predefined. For example, when some worker or equipment blocks the line-of-sight of the robotic total station, the survey process would fail and the system will receive a corresponding error code. In this case, the system automatically reinstates to a safe mode and alerts the operator or the surveyors about the situation.

The fourth problem is communication quality. There are dozens of wireless sensor nodes and the performance of each is influenced by battery, software bug, and other factors of the application setting. Currently, the system watches sending and receiving data from the wireless network, and observe time-out exceptions and message corruptions in communication. If errors and exceptions accumulate rapidly in a short time, the system probably suffers from failure in communication nodes, and such notification will be sent to operator. If the failure happens in a router node, it is more complicated to locate the node and it is not straightforward to identify which router has failed.

The last problem is deployment and it is most difficult to mount the tablet computer. The chamber of the TBM operator is confined and also the body of TBM is heated by all electrical and mechanical systems. Right now the tablet computer is put on the control panel but the heat can cause the tablet to malfunction.

3. EXPERIMENTS

The system was tested in an eight-foot drainage tunnel and field data were collected during the seven-month period from August 2012 to Mar 2013. The tests are divided into two phases: in the first phase, the system surveys the targets for several rounds and each round lasts for one hour, then the surveying results are regularly compared against surveyors’ independent checking results; in the second phase, the system runs continuously in the tunnel while the crew and TBM are working. The robustness of the system integration and automation in the field was tested in the second phase, and the system was capable to realize following functions:

- The wireless network was always online during the tests. The wireless coverage, interference, delay and batteries performed normally during the test. This test is to make sure that design and setup of the wireless network hardware system is valid in the tunnel setting.
- The total station surveyed the target prisms every five minutes. This test is to make sure the total station internal command server performs consistently with the wireless network and the control system.
- The control and computing module handled data and exceptions properly, for example, when the line-of-sight is blocked by anything or anyone, the total station should halt the current survey and a later retry is scheduled.
- The data receiver captured the surveyed data and submitted processed results to the database underpinning the three-dimensional visualization program.

During one field test, the system ran consecutively for two hours, and Table 1 shows the successful survey results. According to the logging system, all messages during the two hours were successfully sent and received, and it shows that the wireless network and the total station worked well in the test. Meanwhile, during the test, the line-of-sight was blocked by workers and the expander of TBM for a relatively long time, and the control system handled the situation properly, resulting in a blank survey history between 10:29 and 11:01. On the other side, the three-dimensional visualization program received computed results, and updated the rendered scene successfully.

Table 1: Continuously survey results of one target prism (H, V are in Radians, D, E, N, Z are in meters)

H	V	D	E	N	Z	Time
3.135	1.569	165.272	27743.705	5934141.545	644.722	13/03/2013 10:15:46 AM
3.135	1.569	165.288	27743.704	5934141.528	644.722	13/03/2013 10:21:36 AM
3.135	1.569	165.34	27743.706	5934141.476	644.721	13/03/2013 10:24:01 AM
3.135	1.569	165.381	27743.703	5934141.435	644.721	13/03/2013 10:25:07 AM
3.135	1.569	165.502	27743.705	5934141.314	644.721	13/03/2013 10:29:37 AM
3.135	1.569	166.1	27743.714	5934140.717	644.719	13/03/2013 11:01:26 AM
3.135	1.569	166.123	27743.714	5934140.694	644.72	13/03/2013 11:02:08 AM
3.135	1.569	166.184	27743.713	5934140.633	644.718	13/03/2013 11:04:16 AM
3.135	1.569	166.286	27743.715	5934140.53	644.721	13/03/2013 11:17:24 AM
3.135	1.569	166.286	27743.717	5934140.531	644.72	13/03/2013 11:19:40 AM
3.135	1.569	166.149	27743.713	5934140.667	644.72	13/03/2013 11:33:35 AM
3.135	1.569	166.149	27743.711	5934140.667	644.722	13/03/2013 11:34:42 AM
3.135	1.569	166.149	27743.713	5934140.668	644.721	13/03/2013 11:36:15 AM
3.135	1.569	166.152	27743.717	5934140.665	644.72	13/03/2013 12:06:51 PM
3.135	1.569	166.151	27743.715	5934140.665	644.722	13/03/2013 12:12:58 PM

Besides the field test, a mock-model based test was also rigorously conducted in a well-controlled lab environment in order to validate the accuracy of the system. As shown in Fig. 6, Point 1 is mounted at the center of TBM cutter head, and Points 2, 3 and 4 are mounted on the rear end of the TBM. In a real tunnel, Point 1 is not visible, and only points at the rear end can be surveyed. Before the test, relative coordinates of all four points were registered and recorded. In the test, every time the position and altitude of the TBM was changed, the total station surveyed the new coordinates of Points 2, 3 and 4, and the corresponding coordinate of Point 1 and the attitude of the TBM were calculated automatically. Then Point 1 was manually surveyed by the total station in the same positioning frame. The resulting coordinates were taken as ground truth to cross check the calculated coordinates, revealing one to two mm differences on average.

Fig. 6: The mockup TBM model for algorithm validation

4. CONCLUSIONS

This research has implemented the Virtual Laser Target Board (VLTB) system design based on an enhanced version of the point-to-angle computing algorithm proposed by Shen and Lu (Shen and Lu, 2012). It provides an accurate and intuitive solution to practicing effective construction engineering and management on tunnel projects. For surveyors, the system is not based on parallelism of the laser to the tunnel alignment, and therefore it is much easier to set up and relocate during construction. Also, the automatic self-check mechanism can report any displacement of the laser station (total station) at the earliest opportunity, reducing the heavy work load of performing regular checks by surveyors. This greatly shortens the time for quality control feedback and surveying tasks will not be necessary to interrupt the tunnel construction, leading to significant improvement in productivity.

And for TBM operators, the system requires no learning curve and provides them a neat and intuitive interface to work with. The interface is elegant and to the point compared with a three-dimensional visualization interface. When the system finds errors or exceptional situations, the operator can be alerted immediately. So the operator can carry out the challenging TBM-steering control measures with more confidence. Furthermore, with benefits of high accuracy and real-time feedback provided by the system, the operators can easily comprehend the TBM position and heading, and plan for optimal steering strategy in the immediate future during construction.

To guarantee system reliability, improving power use efficiency and self-debug ability of the ZigBee wireless sensor network are the issues to be addressed in the future. A possible solution is to change the communication mode from broadcast to point-to-point communication; thus, ZigBee sensor nodes can run on smart power-saving options and have longer battery life. As for the self-debug ability, when point-to-point mode is enabled, the system can iteratively query each sensor node and detect any malfunctioned ones. Nonetheless, the point-to-point mode cannot work directly with the robotic total station. A new system-on-chip control device can be an alternative solution to materialize the two-way wireless communication between a control tablet PC and the robotic total station.

5. ACKNOWLEDGEMENT

This research was substantially supported by Alberta Applied Research Funding program of TECTERRA (1108-UNI-008). The authors thank Mr. Siri Fernando, Mr. Tim Schneider, Mr. Chris Pratt, Mr. Grant Fox, Mr. Rick Edge, Mr. Darsh Wimal Nawaratna, Mr. Michael Yu, Mr. Ray Davis and Mr. Junhao Zou of the City of Edmonton for their help in conducting field trials.

6. REFERENCES

Liang, X. and Lu, Ming. (2010). 3D visualization for tunnel boring machine steering and alignment control in microtunneling, *Proc., 2010 Construction Research Congress*, American Society of Civil Engineers, 1–10.

Miller, R. and Tripathi, A. (1997). Issues with exception handling in object-oriented systems, in Akşit, M. and Matsuoka, S. (Eds.), Springer Berlin Heidelberg, 85–103.

Shen, X. and Lu, M. (2012). Development of Virtual Laser Target Board to Tunnel Boring Machine Guidance Control, *Computing in Civil Engineering (2012)*, American Society of Civil Engineers, 413–420.

tacs GmbH. (2004). tacs acs +++ Summary of the acs guidance system. Retrieved May 2, 2013, from http://www.tacsgmbh.de/en/tacs_prod_acs_overview.htm

tacs GmbH. (n.d.). tacs +++ Video Targets. Retrieved May 2, 2013a, from http://www.tacsgmbh.de/en/tacs_prod_videotargets.htm

tacs GmbH. (n.d.). tacs acs +++ Display of TBM-Position (Example). Retrieved May 2, 2013b, from http://www.tacsgmbh.de/en/tacs_prod_acs_xmpl_tbmpos.htm

VMT GmbH. (2003). SLS-T APD Tunnel Guidance System. Retrieved from http://www.microtunel.com/descargas/slst.pdf

SWAP BASED PROCESS SCHEDULE OPTIMIZATION USING DISCRETE-EVENT SIMULATION

Maximilian Bügler, Gergő Dori & André Borrmann
Chair of Computational Modeling and Simulation – Technische Universität München

ABSTRACT: *Large construction projects usually involve many tasks, which are connected through dependencies and usage of common resources and materials. Determining the optimal order of task execution is in most of the cases impossible to do by hand. Therefore different methods for automatic optimization of large process schedules using a discrete-event simulation system were investigated. This paper introduces a new heuristic method for the resource constrained project scheduling problem, called swap-based optimization. Compared to creating an optimal schedule from scratch, the swap approach facilitates obtaining metrics about the performance of the result, before having worked through the entire construction process. Swaps are introduced into the simulation model by assigning priorities to the tasks. After running a simulation a list of possible swaps is created. Applying one of them and restarting the simulation will introduce a change into the sequence of the tasks within the schedule, generating a different schedule than the one before. Different tree search algorithms, traversing the space of possible swaps throughout a construction process, were analyzed. The suitability of the method is proven by an extensive case study.*

KEYWORDS: *Resource Constrained Project Scheduling Problem, Project Schedule Optimization, Discrete-event Simulation, Task Swaps, Construction Site, Tree search.*

1. INTRODUCTION

Creating schedules for large construction projects involves large numbers of tasks, their respective dependencies, resource constraints and material needs. Also geometric constraints can be taken into account (Marx et al., 2010). Deterministically solving such problems is considered NP-hard (Mingozzi et al., 1998). This paper introduces a new heuristic approach for solving the resource constrained project scheduling problem. In order to efficiently obtain feasible solutions for such a problem, discrete-event simulation can be used. While running a simulation it is possible to obtain a list of tasks that could be swapped while resulting in a new schedule. The proposed approach uses this possibility to create search trees based on those swaps and different search algorithms are investigated and compared to each other.

2. DISCRETE EVENT SIMULATION

A constraint based discrete-event simulation model is used to generate schedules, since it always results in a feasible schedule (Beißert et al., 2007). A scenario is defined by a set of tasks, respective prerequisites, and resource and material requirements. First a list of tasks with no prerequisites is generated. Then one or more of those tasks are executed, depending on the availability of the required resources and materials. The tasks may be prioritized for the selection process. After that the time of the next event is determined by calculating the time the next task is finished. Then a new list of tasks, which have satisfied precedence and resource constraints, is created. This procedure is repeated until all tasks have been executed. The result is a feasible schedule providing metrics that can be used for optimization.

3. SWAP CONCEPT

After creating an initial schedule using the discrete-event simulator, where tasks are randomly selected from the list of executable tasks, a list of possible swaps is created. Each time a task is executed during simulation, it was selected from a list of executable tasks. At this point the list is updated and some other tasks may have to be removed from the list because required resources are now used by the executed task. When this occurs it is possible to swap the executed task with each task that was removed. Over the entire span of the simulation this will result in

---

Citation: Bügler, M., Dori, G. & Borrmann, A. (2013). Swap based process schedule optimization using discrete-event simulation. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

a list of possible swaps for each time step. In order to apply swaps in the simulation the tasks are prioritized. For the base schedule all priorities are selected randomly, or by incrementally numbering all processes. When a swap of two tasks is applied the respective priorities are flipped. In the following simulations the tasks are no longer selected randomly but based on their respective priorities. Fig. 1 shows an illustrative case for a simple project, where arrows indicate dependencies and colors indicate resource usage. Hence tasks B and C use the same resource, so cannot be executed simultaneously. Also, they must be executed after task A has finished. Similarly task D needs task C to be finished. An obvious solution for an execution order for this problem is illustrated in Fig. 2. When applying a swap of tasks B and C, it can be observed that the schedule is shorter, as it is presented in Fig. 3. This shows how the application of swaps can influence the overall project schedule duration.

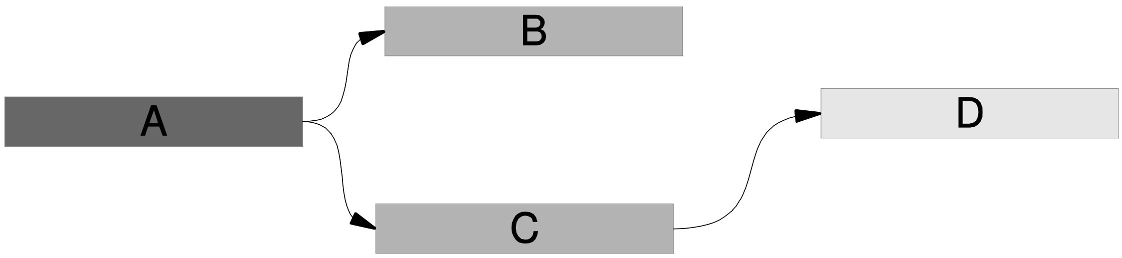


Fig. 1: Dependencies of illustrative case. Colors indicate resource usages and arrows indicate predecessor constraints.

Fig. 2: Possible execution schedule

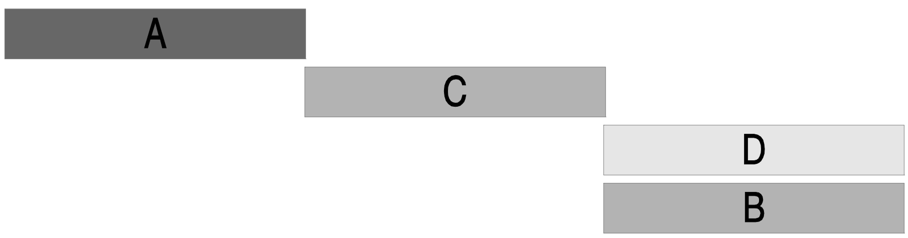


Fig. 3: Execution schedule after swapping B and C

A key advantage of using the swap based approach, compared to building a schedule from scratch, is that simulating the resulting prioritization provides a schedule duration which can be used as a precise score for tree search algorithms.

4. SEARCH APPROACHES

Given a list of possible swaps a search tree can be constructed which covers all possible schedules (see Fig. 4). In practical cases with several thousand tasks though, this tree will grow very large and may therefore be infeasible to search completely. Especially when considering that each application of a swap requires a simulation run to determine the resulting schedule duration. Therefore different ways to traverse the resulting trees have been investigated, using a variety of pruning methods. Pruning describes the removal of specific branches of search trees, according to some criteria (Mansour, 1997). Since the optimization starts from a single random solution a single tree branching out from this initial solution (root node) is created. Each child of the root node represents the application of a single swap. Each further level down the tree incorporates additional swaps. The simplest possible approach is greedy search is to only look for the most beneficial swap at each level, if such a swap exists (Black et al., 2005). Hence the branching only takes place on the single most beneficial swap, after which this procedure is repeated until no more improvements can be found. The downside of this approach is that there are cases where a non-beneficial swap allows for another swap that will result in a shorter duration as the initial solution. Such a case is illustrated in Fig. 5, which shows dependencies between five tasks A through E. A schedule created from these dependencies is illustrated in Fig. 6. Applying a swap between tasks B and C increases the execution duration significantly by preventing any parallel execution of tasks. This is shown in Fig. 7. The additional application of a swap between A and E now allows parallel execution of A and C and therefore results in a shorter execution time compared to the initial schedule of Fig. 6. The final schedule is illustrated in Fig. 8.

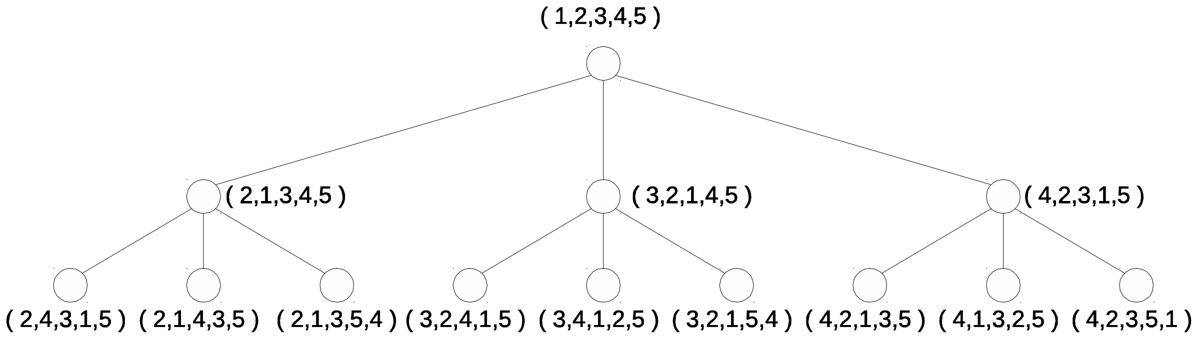


Fig. 4: Search Tree Illustration. The vectors contain the priorities of the tasks.

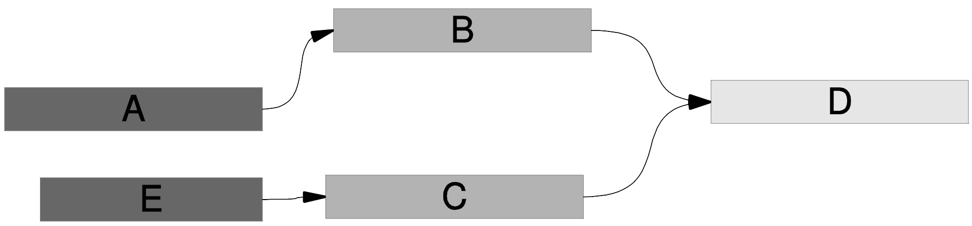


Fig. 5: Dependencies of illustrative case 2. Colors indicate resource usages and arrows indicate predecessor constraints.

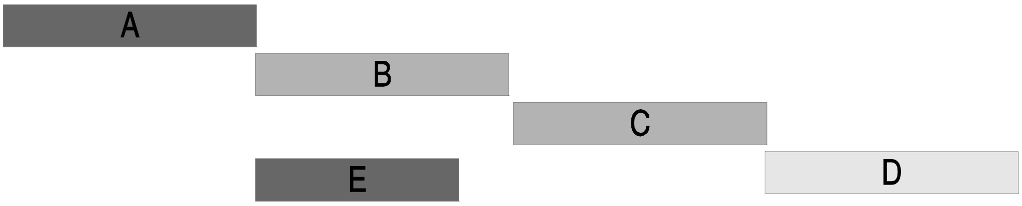


Fig. 6: Possible execution schedule

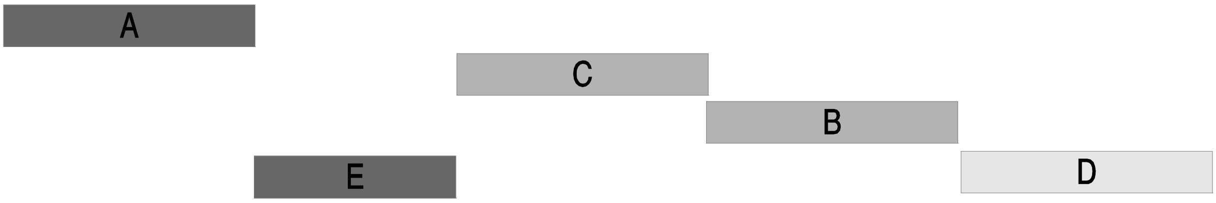


Fig. 7: Longer schedule after applying one swap of B and C

Fig. 8: Shorter schedule after applying swaps between B, C and A, E

In order to incorporate solutions where multiple swaps, which each at its own are non-beneficial, applied together give a better solution a less radical way to prune the search tree is required. A simple measure to realize this is by introducing a tolerance factor. This means that instead of stopping when no more beneficial swaps can be found, also swaps which increase the overall execution by a certain tolerance amount are taken into account. While in the case illustrated in Fig. 5, this tolerance amount would need to be quite large, the ratio by which the swap prolongs the schedule in larger problems is expected to be much smaller. A problem arising with this approach is that there are many swaps that may result in delays below the tolerance ratio, and the search tree therefore may expand quite strongly. Therefore it will in large cases become infeasible to perform a full search of the tree. A useful assumption would be that longer series of non-beneficial swaps become less likely to yield a benefit. This assumption allows splitting the search tree into segments of limited depth. For instance assuming that there is no beneficial series of more than k non-beneficial swaps would allow only searching the tree to a depth of k while being very tolerant. Then the best solution from the limited-depth search tree is selected and a new search tree is built, using the solution as a new root node. Each segment of this search tree will therefore be limited to n^k leaf nodes, where n is the number of possible swaps.

Another way to traverse the search tree is simulated annealing, which is inspired by the solidification of matter when cooling down (König et al., 2009). This approach was modeled by introducing a temperature value starting at a value of 1 and reducing over time by a certain decay rate, between 0 and 1. The decay is applied after each depth level in the implementation used. The temperature value is used as the probability of accepting an inferior swap. It can therefore be interpreted as tolerance. At some point no more change takes place, when the process can be stopped.

An issue that generally can arise during traversal of the resulting search trees is revisiting the same state multiple times. It is of course desirable to prevent this from happening. Therefore tabu-search was applied to the search processes. Tabu-search means verifying whether a new state is practically equal to a previously encountered state and therefore investigating it is redundant (Glover et al., 1989).

5. CASE STUDY

In order to test and compare the proposed methods a case study has been performed. The scenario that was analysed consists of two connected walls of drill pines and and four excavation areas. Each drill pine needs three tasks to be built. First a hole needs to be drilled. This task requires one worker to operate the drill. Afterwards three workers and a crane are necessary to insert the reinforcment cage into the hole. Furthermore two workers and a concrete pump are required to fill the hole with concrete. Finally the top of the pine needs to be grinded flat, requiring one worker and a grinding machine. Since the pines are overlapping, the cropped pines, need to be placed before the others. When all drillpines connected to an excavation area are finished, the excavation can be started. This requires one worker and an excavator to be available. The scenario is finished when all tasks are executed. Additionally the areas blocked by the tasks and the employed machines are taken into account during simulation. The scenario is illustrated in Fig. 9. In order to evaluate the results of the tested approaches, a Mixed-Integer-Linear-Programming (MILP) formulation of the problem has been solved to obtain an exact solution to the problem (Konéa et al., 2011). The optimal solution is illustrated in Fig. 12, located in the appendix.

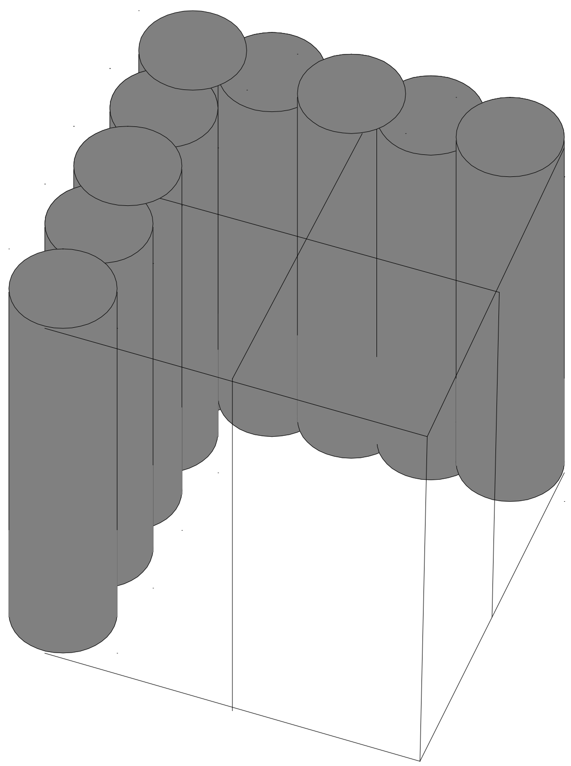


Fig. 9: Scenario used for Case Study. The grey cylinders represent drill pines and the squares represent the four excavation areas.

As an objective, the minimization of the overall execution time of the resulting schedule was used. It would also be possible to use any other metric obtained through simulation for the search algorithms. Table 1 shows the results obtained from the different algorithms. The processing times were all measured using an Intel Core i7-3520M

CPU while utilizing all cores. The greedy approach is very fast, but gives suboptimal results. Next simulated annealing was tested using different levels of decay, where 1 is no decay and 0 is immediate decay, so equal to the greedy method. The optimal solution was found with decay values of 0.7 and higher, requiring 21 minutes of processing time. But also with strong decay, the result was near optimal and the processing time was very low. The limited depth series approach returned the optimal solution starting at depth 3, so it was not necessary to apply more than 3 non beneficial swaps in this scenario, to find the optimal solution. Finally the tree search with tolerance was evaluated with different tolerance levels of up to 10%. The optimal solution was not found here. The comparisons of the performances are illustrated in Fig. 10 and Fig. 11.

The limited depth series approach required the lowest number of simulations and therefore was fastest in finding the optimal solution for the problem, followed by the simulated annealing algorithm. The tolerant search approach was increasing in complexity very quickly. With tolerance values above 10% the processing time exceeded several hours. But the result returned with 10% tolerance is not very far off the optimal solution and was processed very quickly, so this might still be a reasonable heuristic.

Table 1: Comparison of search algorithms

Algorithm	Parameter	Resulting Schedule duration	Number of Simulations performed	Required time
Greedy		147h	117	746ms
Simulated Annealing	Decay=0.4	119h	11903	2.8s
Simulated Annealing	Decay=0.6	119h	674561	73.7s
Simulated Annealing	Decay=0.7	118h	11264258	1255.7s
Limited Depth Series	Depth=1	147h	39	476ms
Limited Depth Series	Depth=2	123h	3189	2s
Limited Depth Series	Depth=3	118h	85171	11.8s
Limited Depth Series	Depth=4	118h	3616705	384.3s
Tolerant search	Tolerance=1%	147h	197	712ms
Tolerant search	Tolerance=5%	123h	6064	4.9s
Tolerant search	Tolerance=10%	123h	192245	21.8s
MILP Solver		118h		10h

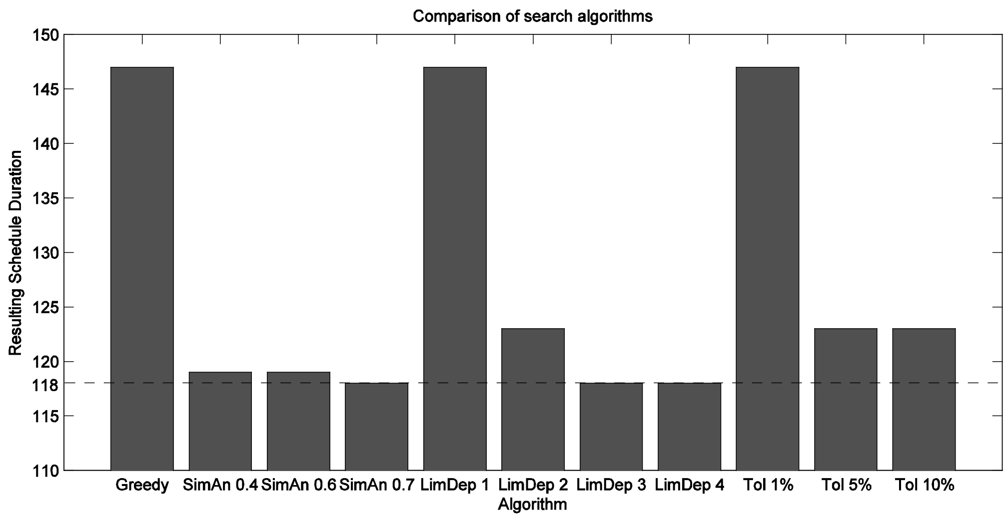


Fig. 10: Result comparison of search algorithms

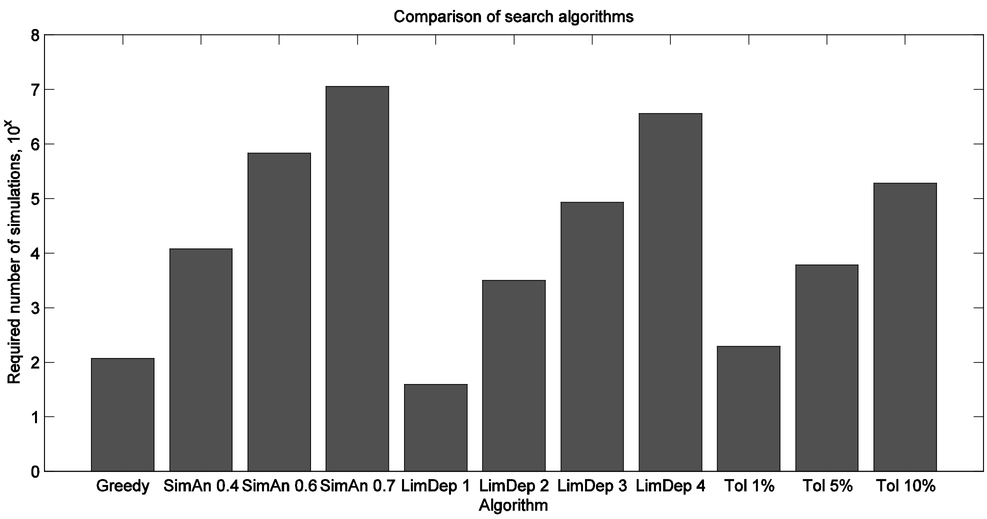


Fig. 11: Number of simulations needed for the different search algorithms

6. PITFALLS

A major pitfall encountered during analysis of the approach was the necessity of using tabu-search. Due to the huge number of simulations that need to be performed, the memory demands for book keeping of the evaluated states was very high. Furthermore the application of a swap can drastically change the entire schedule after the time of the swap. This can cause the algorithms to randomly traverse the search space, making pruning more difficult. In the scenarios that were evaluated so far, this did not impose a major obstacle, though.

7. CONCLUSIONS

This paper introduced a new heuristic approach for solving the resource constraint project scheduling problem. Search trees were constructed from possible task swaps, obtained through constraint based discrete-event simulation. The proposed approach returned very good results in the studied case. Among the algorithms that were tested, simulated annealing and the limited depth series search performed best and returned the optimal solution in much shorter time than the MILP approach used for benchmarking. Though there can be cases where the tolerant search algorithm would also return good results. In order to evaluate this, further research is required. More complex case studies will be performed to test whether the results are consistent among different kinds of projects. Further experiments are required to determine the number of non-beneficial swaps that can still be beneficial in large scale projects.

8. REFERENCES

Beißert U., König M., Bargstädt H.-J. (2007). Constraint-Based Simulation of Outfitting Processes in Building Engineering, in: *Proceedings of CIB w78 Conference, Maribor, Slovenia*

Black, P. E. (2005). Greedy Algorithm. Published electronically, *Dictionary of Algorithms and Data Structures. U.S. National Institute of Standards and Technology (NIST).*

Dori G., Borrmann A. (2011). Automatic generation of Complex Bridge Construction Animation Sections by coupling Constraint-based Discrete-Event Simulation with Game Engines. *Proceedings of CONVR - International Conference on Construction Applications of Virtual Reality, Weimar, Germany, 2011*

Glover F. (1989). Tabu Search - Part 1. *ORSA Journal on Computing 1 (2): 190–206.*

Konéa O., Artiguesa C., Lopeza P., Mongeauc M. (2011). Event-based MILP models for resource-constrained project scheduling problems. *Computers & Operations Research Volume 38, Issue 1, January 2011, Pages 3–13*

König M., Beißert U. (2009). Construction Scheduling Optimization by Simulated Annealing. *Proceedings of the 26th International Symposium on Automation and Robotics in Construction (ISARC 2009)*

Mansour, Y. (1997). Pessimistic decision tree pruning based on tree size. *Machine Learning – International Workshop then Conference. Pages 195-201*

Marx A., Erlemann K., König M. (2010). Simulation of Construction Processes considering Spatial Constraints of Crane Operations. *Proceedings of the XIIIth International Conference on Computing in Civil and Building Engineering*

Mingozzi A., Maniezzo V., Ricciardelli S. Bianco L. (1998). An Exact Algorithm for the Resource-Constrained Project Scheduling Problem Based on a New Mathematical Formulation. *Management Science May 1998 vol. 44 no. 5 714-729*

Robinson S. (2004). Simulation - The practice of model development and use. *Wiley, p. 15-24*

9. APPENDIX

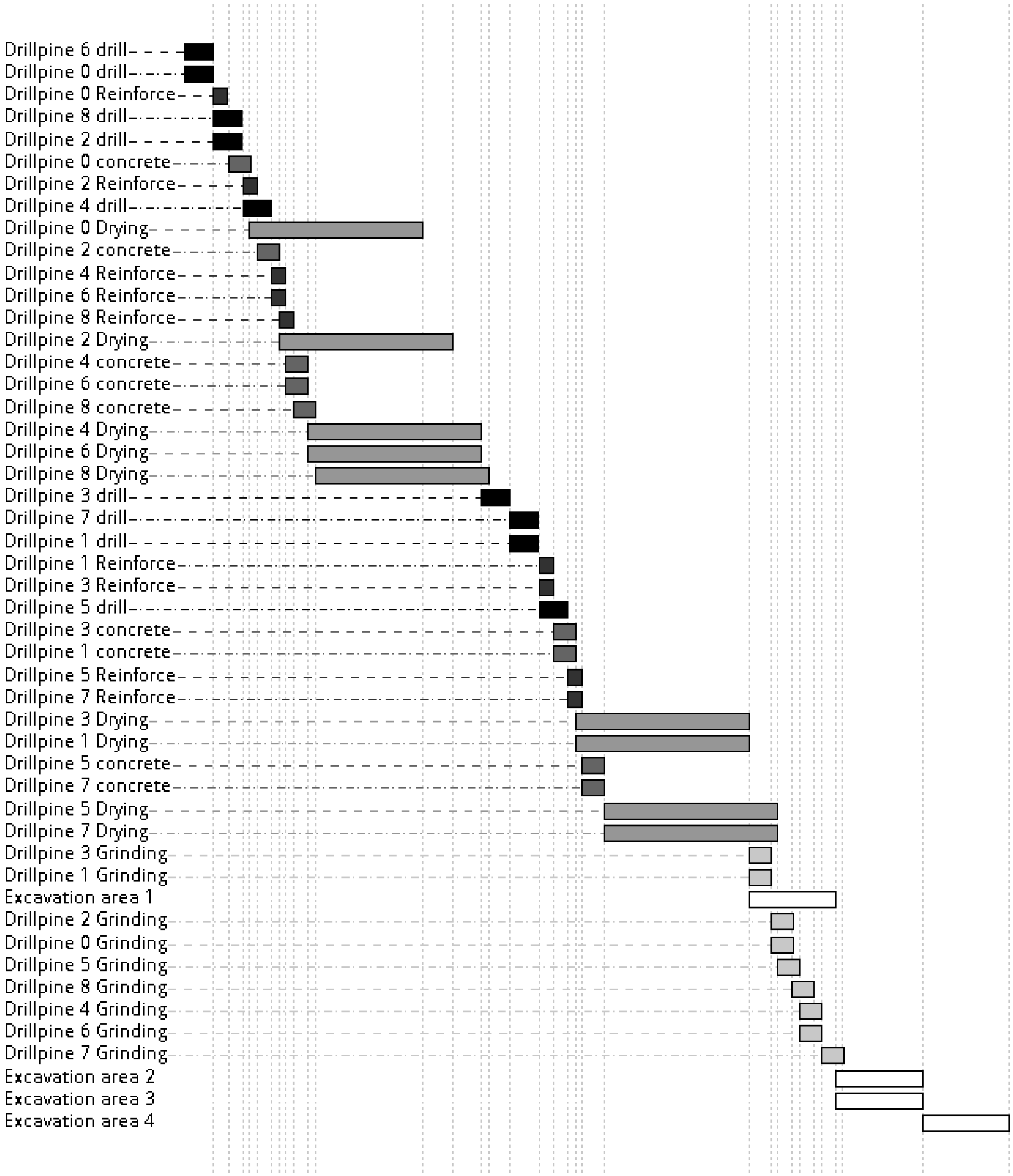


Fig. 12: Optimal Schedule for Case Study Scenario

EFFECTIVE PROJECT SCHEDULING UNDER WORKSPACE CONGESTION AND WORKFLOW DISTURBANCE FACTORS

Vitaly Semenov, Anton Anichkin, Sergey Morozov, Oleg Tarlapan & Vladislav Zolotov
Institute for System Programming RAS, Russia, Moscow

ABSTRACT: *Effective project management implies the use of advanced planning and scheduling methods that allow to determine the feasible sequences of activities and to complete a project on time and on budget. Traditional scheduling tools like fundamental Critical Path Method (CPM) and various methods for Resource Constrained Project Scheduling Problem (RCPSP) and Time Constrained Project Scheduling Problem (TCPSP) have many shortcomings for the construction projects where spatial factor plays critically important role. Previously taken attempts to interpret space as a specific resource were successful for particular problems of line-of-balance scheduling, space scheduling, dynamic layout planning, horizontal and vertical logic scheduling, workspace congestion mitigating, scheduling multiple projects with movable resources, spatial scheduling of repeated and grouped activities, motion planning. However, none of these methods considers the spatio-temporal requirements in a holistic framework of generic RCPSP problem and provides feasible results accounting for workspace and workflow factors. In the paper we start with the classical RCPSP statement and then present mathematically strong formalization of the extended generalized problem taking into account workspace congestion and workflow disturbance constraints specified in practically meaningful and computationally constructive ways. For the generalized RCPSP problem an effective scheduling method is proposed. The method tends to minimize the project makespan while satisfying timing constraints and precedence relations, not exceeding resource utilization limits, avoiding workspace congestion and keeping workflows continuous. The method reuses so-called serial scheduling scheme and provides for additional computational routines and heuristic priority rules to generate feasible schedules satisfying all the imposed requirements. Advantages of the method and prospects for its application to industrial needs are outlined in the paper too.*

KEYWORDS: *planning and scheduling, resource-constrained project scheduling problem, priority rules, 4D modeling, workspace management.*

1. INTRODUCTION

Effective project management implies the use of advanced planning and scheduling methods that allow to determine the feasible sequences of activities and to complete a project on time and on budget. Critical Path Method (CPM) and various methods for Resource Constrained Project Scheduling Problem (RCPSP) and Time Constrained Project Scheduling Problem (TCPSP) are traditional tools incorporated in most popular project management systems like Microsoft Project, Oracle Primavera, Asta Powerproject.

Developed in the 1950s, the CPM generates useful information about the project, such as the longest sequence of activities, the shortest project duration, and the total and free floats of each activity. This information is crucial to a project's success and substantially important for the project manager to plan and control it more actively and efficiently. In the main, critical activities having zero floats should receive the management attention that might be unnecessary on other activities. This management by exception is an important advantage of the CPM, especially on large, complex projects (Ahuja, 1976; Bowers, 1995). Later the original CPM formulation was generalized to take into account resource limitations within the RCPSP and TCPSP statements. In the most of real industrial projects, scheduling without considering these limitations may lead to non-credible results, since the execution of activities is strongly affected by resource availability. Various analytical and heuristic methods have been developed to apply the resource availability into the scheduling process (Ahuja, 1976; David and Patterson, 1975; Hegazy, 1999). Analytical methods attempt to find the optimum solution in terms of the minimum project duration, but usually require very long computational time, making them impractical. On the other hand, heuristic approaches provide reasonable solutions for large-scale projects in practical time (Boctor, 1990; Hegazy, 1999).

Citation: Semenov, V., Anichkin, A., Morozov, S., Tarlapan, O. & Zolotov, V. (2013). Effective project scheduling under workspace congestion and workflow disturbance factors. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

However, these methods ignore divergent spatial factors and cannot guarantee the correctness of the prepared schedules in terms of lack of spatial conflicts commonly related to workspace congestion and workflow disturbance. Indeed, an activity can be performed if only all the needed workspaces are reserved throughout its execution period and if they are not occupied by other competitive activities arranged at the same place at the same time. In some sense, workspaces can be interpreted as renewable resources shared among concurrent project activities with predefined utilization rates. This observation applies equally to the spaces required to install or to assemble product components, to store materials on logistics sites, the spaces used as passageways to deliver resources to destination areas or reserved for parking zones or household rooms, the spaces preventing safety hazards. The workflow disturbance is another factor preventing prompt movement of resources on a project site, increasing idle time for labour and equipment, and thereby, deteriorating their productivity. To allow for cost and time efficiencies, it is necessary to achieve workflow continuity by balancing the resource utilization and replacement.

Many researchers addressed to these topics by means of the introduced concepts of line-of-balance (LOB) scheduling (Siddesh K Pai, Preeti Verguese and Shweta Rai, 2013), space scheduling (Choo and Tommelein, 1999), dynamic layout planning (Zouein and Tommelein, 1999), horizontal and vertical logic scheduling (Thabet and Beliveau, 1994b), workspace congestion mitigating (Yeoh and David, 2012), scheduling multiple projects with movable resources (Hegazy, 1999), spatial scheduling of repeated and grouped activities (Thabet and Beliveau, 1994a), motion planning (Ellips and Davoud, 2007). However, these attempts were successful only for very particular statements as well as did not result in a holistic framework accounting for workspace and workflow factors and extending traditional CPM, RCPSP and TCPSP methods.

In particular, the LOB is a linear scheduling method that allows balancing of the operations in the projects with repeated activities continuously performed in each consecutive unit. Repeating units are commonly found as typical floors in high rise buildings, residences in multi-housing developments, stations in highways, meters in pipeline network, long bridges, tunnels, railways, or water mains. Using the LOB, the repetitive activities are scheduled in such a way to ensure a smooth procession of resources from unit to unit with minimal conflicts. However, many researches indicated that this technique is suitable to model simple repetitive production processes, but it is quite limited for the complex projects represented by discrete activities with varied utilization and productivity rates.

In the paper alternative scheduling formulations are discussed to extend the classical CPM and RCPSP statements and to account for workspace and workflow factors. In the Section 2 we start with the classical statements and then provide mathematically strong formalization of the generalized problem with the workspace congestion and workflow disturbance constraints specified in practically meaningful and computationally constructive ways. An effective scheduling method for the generalized problem is presented in the Section 3. The method tends to minimize the project makespan while satisfying timing constraints and precedence relations, not exceeding resource utilization limits, avoiding workspace congestion and keeping workflows continuous. The method reuses so-called serial scheduling scheme and provides for additional computational routines and heuristic rules to generate feasible schedules satisfying all the imposed requirements. The Section 4 is devoted to preliminary validation of the method. In the Conclusions advantages of the method are summarized and prospects for its application in industrial practice are outlined.

2. GENERALIZED SCHEDULING PROBLEM

2.1 Classical RCPSP formulation

The classical RCPSP problem can be stated as follows. A single project can be represented by a network with N activities on the nodes and M links on its arcs. Every activity a_n, $n = 1,...,N$ implies an uninterrupted process beginning at the time t_n and having the fixed duration $d_n \geq 0$. Every link l_m, $m = 1,...,M$ reproduces the finish-start precedence relation between a predecessor activity $a_{Pr(m)}$ and a successor activity $a_{Sc(m)}$ and forces the successor activity not to be started earlier than the given lag τ_m after its predecessor has been finished. A successor activity having only zero-lag links cannot start until all its predecessors have been finished. For the formalization unique dummy source and sink activities a_1 and a_N of zero duration $d_1 = 0$, $d_N = 0$ are introduced and they are linked with the project activities having opened starts and opened ends respectively. In order to be processed, an activity a_n may require u_{nk} units of the renewable resource r_k during its execution. A constant availability of every resource r_k, $k = 1,...,K$ is assumed and denoted as U_k. In correctly scheduled plan it cannot be exceeded at any time point t such that $t_1 \leq t \leq t_n$ throughout the whole project. In order to make the problem simple, activity splitting and resource levelling are not considered. The objective of the RCPSP is to schedule the activities such that the makespan of the project is minimized, all the precedence relations are satisfied and resource availability limits are not exceeded. Let $A(t)$ denotes an index set of the activities being in progress at the time t or formally $A(t) = \{n \mid n = 1,...,N, t_n \le t < t_n + d_n\}$, then the RCPSP problem can be mathematically formulated for unknown variable $X = \{t_n\}_{n=1}^{N}$ as follows:

$$\min t_N \text{ subject to} \tag{1}$$

$$t_{Sc(m)} \ge t_{Pr(m)} + d_{Pr(m)} + \tau_m, \forall m = 1,...,M \tag{2}$$

$$\sum_{n \in A(t)} u_{nk} \le U_k, \forall k = 1,...K, \forall t \mid t_1 \le t \le t_n \tag{3}$$

The objective function (1) minimizes the completion time of the unique sink activity t_N and thereby the makespan of the whole project. Constraints (2) take into consideration the links between each pair of preceding and succeeding activities. Finally, constraints (3) limit the total resource utilization at each time point to the available amounts. To be correct from mathematical point of view and to guarantee the solution existence, the RCPSP must avoid any link cycles and exclude exceeded resource utilization for individual activities so that $u_{nk} \le U_k, \forall n = 1,...,N\ \forall k = 1,...,K$.

By relaxing the resource constraints (3), the RCPSP reduces to the CPM-case which can be solved by forward recursion in polynomial time. But in general statement the RCPSP belongs to the class of NP-hard problems (Kolisch, Sprechrr and Drexl, 1995; Lavalle, 2006). Existing dynamic programming procedures as well as the branch and bound techniques are too computationally expensive to find optimal solutions in most practical cases. Therefore, heuristic approaches, and in particular, priority rule based scheduling methods, are usually employed within commercial packages for such purposes. Generally, such methods distinguish in a scheduling scheme (serial or parallel, single- or multi-pass) and in a set of rules to prioritize the concurrent activities which over-consume the limited resources. Well-known priority rules are most total successors (MTS), latest start time (LST), greatest rank positional weight (GRPW), weighted resource utilization ratio and precedence (WRUP), latest finish time (LFF), minimum slack (MSLK). Being combined and implemented within multi-pass schemes, they show the best results obtainable by heuristics today. For more details, please see (Kolisch, Sprechrr and Drexl, 1995).

2.2 Workspace congestion conditions

As stated above, the RCPSP only takes into account constraints for renewable resources. It can be extended by introducing workspaces that allow explicit visual interpretation and mathematically strong formalization. Let w_i, $i = 1,...,I$ are project workspaces geometrically represented by solids being connected, compact, orientable 3-dimensional manifolds in Euclidean space. Typically they are the objects of simple shape: cuboids, cylinders, prisms, pyramids, spheres, cones, polyhedra. But they can be compound objects constructed from primitives by means of Boolean operations on sets: union, intersection and difference. Being adopted by the constructive solid geometry modeling (CSG), these operations are traditionally denoted as $\cup$, $\cap$ and $\setminus$ respectively. Workspaces can overlap each other in different dimensions and across time and therefore they cannot be considered as independent resources.

By consuming u_{nk} units of the resource r_k with corresponding spatial rate v_k and operational time d_{nk}, the activity a_n utilizes a workspace $w_{i(n,k)}$ with the factor

$$\rho_{nk}(t) = \begin{cases} u_{nk} \dfrac{v_k}{v(w_{i(n,k)})} \dfrac{d_{nk}}{d_n} & \text{if } t_n \le t < t_n + d_n \\ 0 & \text{otherwise} \end{cases}, \tag{4}$$

where the function $v(w)$ returns the volume of the corresponding workspace. The introduced factor can be interpreted as an averaged density of the resource units per unit volume per unit time. A spatial multiplier in the expression gives a ratio of the space required by the resource unit to the total available space allocated to the activity. A temporal multiplier reflects the fact that workspaces may not always be utilized throughout the activity's operation time and may be used to describe the intermittent nature of continuous activities. A notation

$w_{i(n,k)}$ is used here to emphasize that the workspace w_i is associated with the activity a_n and the related resource r_k only when the activity performs.

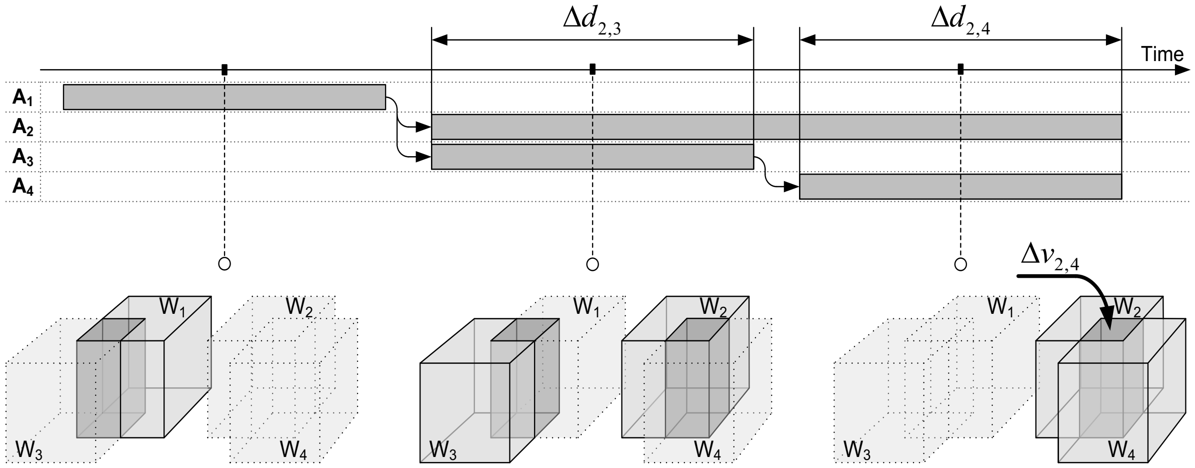


Fig. 1: Example of workspace competition.

Two workspaces $w_{i(n,k)}$, $w_{i'(n',k')}$ are defined as interfering ones if their originating activities overlap in a time interval $\Delta d_{n,n'} > 0$ and their solids intersect in a volume $\Delta v_{i,i'} = v(w_{i(n,k)} \cap w_{i'(n',k')}) > 0$. Then the workspace interference can be quantified by multiplying these factors. To be processed concurrently the activities must avoid workspace competition and congestion. By limiting the utilization and congestion factors we thus require that the workspace capacity must be large enough to allocate all the needed amount of the resource units, including units allocated in other interfering workspaces. In other words, the conflicting activities should have an opportunity to be rearranged so that the utilized resources can be reallocated over free domains of the workspaces. Under the suggestion that workspaces are consumed by different activities and resources additively, this requirement takes the following form:

for $\forall i(n,k) \in I(A,U)$, $\forall t \mid t_n \le t < t_n + d_n$

$$\sum_{(n',k') \in I(A,U)} \rho_{n'k'}(t)\, v(w_{i(n,k)} \cap w_{i'(n',k')})\, \Delta d_{n,n'} \le v(w_{i(n,k)})\, d_n , \tag{5}$$

where $I(A,U)$ is a set of index pairs for all the activities and related resources so that $u_{nk} \ne 0$. The constraint (5) is stated for every workspace $w_{i(n,k)}$ throughout the execution interval of its originating activity $t_n \le t < t_n + d_n$. A summation on the left side of the constraint is taken over all the project workspaces, including the given workspace. It is essential that the constraints (5) allow short-term intersecting or even overlapping of workspaces on the condition that their utilization and congestion factors are small enough.

Consider a sample schedule consisting of four activities A_1–A_4, each of them utilizes own workspace W_1–W_4 correspondingly. The workspaces are represented by solids having simple box shape and being located as shown by the Figure 1. In spite of solids of the workspaces W_1, W_3 as well as W_2, W_4 intersect, the figure demonstrates the only case of competition and potential congestion of the workspaces W_2, W_4 introduced by the activities A_2 and A_4 overlapping in the time interval $\Delta d_{2,4} = [t_4, t_4 + d_4]$. The workspaces W_1, W_3 never interfere each other as the associated activities A_1, A_3 are not performed concurrently according to the schedule. To detect if the activities A_2, A_4 should be rearranged the additional analysis of utilization and congestion factors for the workspaces W_2, W_4 is required.

Often, the operational factor is removed from the consideration and, thereby the resources are suggested to be utilized throughout the whole activity duration. Then, the constraints take the following simplified form:

$$\text{for } \forall i(n,k) \in I(A,U) \quad \sum_{(n',k') \in I(n,k)} u_{n'k'} \frac{v_{k'}}{v_{(n',k')}} v(w_{i(n,k)} \cap w_{i'(n',k')}) \le v(w_{i(n,k)}) \tag{6}$$

A summation on the left side of the constraint is taken over all the workspaces $I(n,k) \subseteq I(A,U)$ interfering with the given workspace $w_{i(n,k)}$. In order to guarantee the existence of a solution, the constraints (5) and (6) being applied to workspaces occupied by every individual activity must be satisfied.

Noteworthy, different models for quantifying spatio-temporal interference between workspaces have been proposed (Yeoh and David, 2012). The formalized constraint (5) is quite similar to the model discussed in (Chua, Yeoh and Song, 2010), while the form (6) is more close to the criteria presented in (Chavada, Dawood and Kassem, 2012). Indeed, if three activities A_1, A_2, A_3 utilize the same resource r in the same workspace w throughout the same duration with respective factors ρ_1, ρ_2, ρ_3, the workspace mitigation requirement takes the trivial form $\rho_1 + \rho_2 + \rho_3 \leq 1$. The general forms (5), (6) are intended for more sophisticated cases when concurrent activities partially overlap in time and utilise different resources allocated in different, partially crossed workspaces.

Main disadvantage of the reduced representation (6) compared with the general form (5) is that even a short time overlay of the workspaces with relatively high utilization factors may lead to a breach of the congestion conditions although unlikely that such workspace conflicts could not be resolved in practice. Nevertheless, in this paper the form (6) is used as more solid requirement imposed upon the interfering workspaces. Moreover, it requires less computation which is especially attractable for scheduling of large projects.

2.3 Workflow disturbance conditions

Workflow continuity is another important factor affecting the schedule feasibility and its practical value. Being arranged in different places (sometimes, in different sites or even in geographically remote regions) the project activities need the resources to be reallocated and replaced in proper workspaces. Regardless of how resources are moved, these factors add on project costs and duration inevitably. Ignoring these factors, the methods usually generate schedules with high resource traffic and unreasonable discontinuous workflows what makes them useless for practical purposes. This is a serious shortcoming of classical CPM, RCPSP, TCPSP methods for properly modelling the real-world constraints.

Unfortunately, the studies mentioned above did not result in common vision on the workflow phenomenon and did not provide a solid basis to specify workflow constraints in a formal way. In this section own model for workflow management is presented being tightly connected with issues of the spatio-temporal allocation of resources among workspaces. The model assumes the permanent use of a global pool of resources and local resource pools associated with separate workspaces. The global project pool stores the total amount of units for each resource type available at the current time. Local pools store similar amounts of units assigned to every workspace individually. At the initial time moment all the resource units are assigned to one or more workspaces emulating logistics sites, warehouses, parking zones or household rooms. Whenever a new activity starts and requests a fixed number of resource units, it should be taken into account not only the availability of the required units at the given time moment, but also their distribution over workspaces. If the requested units are available, the key issue arisen here is which workspaces the resources should be supplied from. Once the decision is made, global and local pools are updated properly so that the total amount of the resource units is decreased by the utilized amount. When the activity is complete, these units are released and placed in the same workspace where they have been utilized by the activity before. As they become available for other activities, the global pool and local pool of this workspace are updated so that the total amount of the available resource units is increased by the released amount.

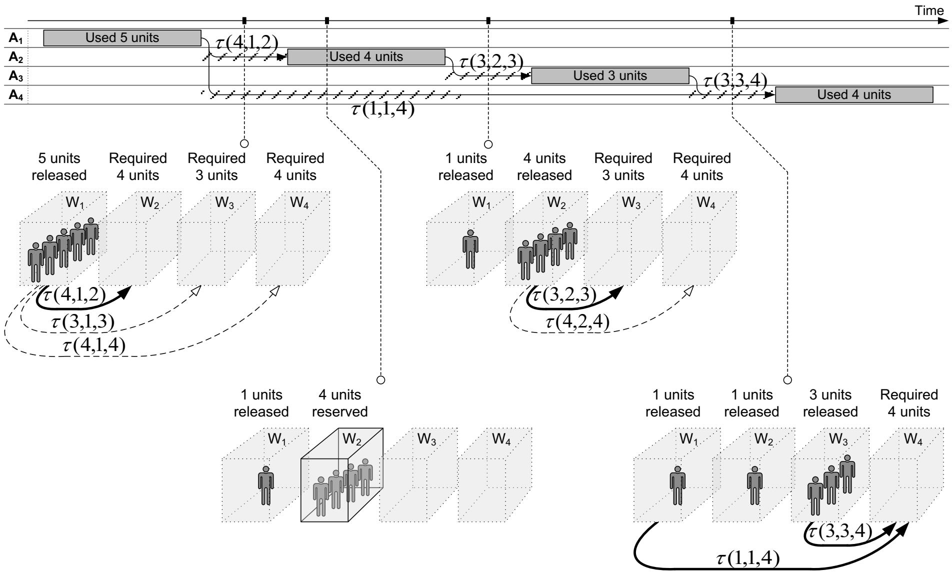


Fig. 2: Example of a schedule taking into account workflow continuity factor.

It is seen the following tight relationship between resource flows and workflows in the scope of the model above. By supplying resource units from the nearest workspaces and minimizing resource reallocation time, the workflows become more regular. The reallocation processes can be simulated by additional links between the activities releasing and consuming the same resource units. Lag of every such link could be determined by means of an user-defined transfer function $\tau^k(\Delta u, i', i'')$ that returns the time needed to move Δu units of the resource r_k from the source workspace $w_{i'}$ to the destination workspace $w_{i''}$. If the activity a_n requires u_{nk} units of the renewable resource r_k and these units can be delivered from the workspaces of the finished activities a_{n_1}, a_{n_2}, …, a_{n_M} so that $u_{nk} = \Delta u_{nk}^{n_1} + \Delta u_{nk}^{n_2} + ... + \Delta u_{nk}^{n_M}$, a structure $\overline{u}_{nk} = \left\{ \Delta u_{nk}^{n_m} \right\}_{m=1}^{M(n,k)}$ is called the route for the resource r_k in conformity to the activity a_n. Then additional transfer links should be created with the conditions below:

$$\text{for } \forall n = 1,...,N,\ \forall k = 1,...,K,\ \forall m = 1,...,M(n,k) \quad t_n \geq t_{n_m} + d_{n_m} + \tau^k(\Delta u_{nk}^{n_m}, i(n_m, k), i(n,k)) \tag{7}$$

Unfortunately, such links cannot be defined by the planner in advance in the problem statement phase and need to be determined directly when the project is being scheduled. Every created transfer link may delay the successor activity and therefore adds on overall project duration. The scheduling methods for thus formalized problem should take into account these circumstances when deciding on the activity priority minimizing the total project makespan and on the resource reallocation policy not disturbing natural workflows.

The Figure 2 presents an example of a schedule taking into account workflow continuity factor. The schedule consists of four activities A_1–A_4 utilizing non-intersecting workspaces of simple box shape W_1–W_4 correspondingly and requiring for execution the given amount of units of a labour resource "worker" as shown over the activity symbols at the Gantt chart. Let a crew consisting of five workers is available to perform activities on the schedule. The work starts with the activity A_1 using all the crew (5 units) that is located at the workspace W_1. After the activity A_1 has been completed all the resource units become available for other activities of the schedule. Analysis of time values returned by transfer functions $\tau(4,1,2)$, $\tau(3,1,3)$, $\tau(4,1,4)$ determines the minimum as $\tau(4,1,2)$ moving 4 workers from W_1 to the closest workspace W_2. Then the precedence relationship between the activities A_1 and A_2 is established so that A_2 should be started just after A_1 has been finished. A_2 reserves 4 resource units moved to the workspace W_2. 1 resource unit has been left released and located in the workspace W_1. No more activities can be started concurrently with A_2 because of lack of sufficient free resource units to perform them.

Similarly, the activity A_3 is scheduled after A_2 has been completed. 3 workers necessary to perform it are reserved and moved to the workspace W_3. 2 workers (one in W_1, another one in W_2) are released, but this is not enough to start the activity A_4 concurrently. Finally, after the activity A_3 has been completed, A_4 requiring 4 resource units can be started. 3 units are moved from the closest workspace W_3, one more unit can be moved either from the workspace W_1 or W_2. In spite of the workspace W_1 is outermost to W_4, the resource unit located in it has been released earlier, so the time value $\tau(1,1,4)$ is less than $\tau(1,2,4)$. Then two precedence relationships between the activities A_1 and A_4 as well as A_3 and A_4 should be defined in the schedule.

3. SCHEDULING METHOD

As mentioned above, the objective of the RCPSP is to schedule the activities such that the makespan of the project is minimized (1), all the precedence relations are satisfied (2) and resource availability limits are not exceeded (3). The unknown variable of the problem is a vector of activity start times $X = \{t_n\}_{n=1}^{N}$. The generalized Workspace and Workflow Constrained Project Scheduling Problem (WWCPSP) can be introduced as a project makespan minimization problem (1), (2), (3) with the additional constraints on workspaces and workflows (6), (7). It is worth noting that the solution of the generalized problem includes not only activity start times, but also resource reallocation routes which would enable the activities to start on the scheduled times. Thus, the unknown variable of the WWCPSP problem is a structure $X = \left\{t_n, \{\overline{u}_{nk}\}_{k=1}^{K}\right\}_{n=1}^{N}$. Generalizing the RCPSP, the WWCPSP remains to be a NP-hard problem and requires long computation time even for finding suboptimal solutions. Let discuss the proposed scheduling method for the WWCPSP. The method adopts so-called serial scheduling scheme and provides for additional computational routines and heuristic rules to generate feasible schedules satisfying all the imposed requirements.

3.1 Scheduling scheme

To resolve the WWCPSP problem the serial scheduling scheme mentioned in many works (Kolisch, 1996b) was adopted and advanced. It assumes a stage-wise algorithm extending a partial schedule (i.e. a schedule where only a subset of the activities has been scheduled and assigned a start time). Two disjoint activity-sets are associated with each stage, namely: the scheduled set *S* and the decision set *D*. The set *S* is formed by indices of the activities which were already scheduled and thus belong to the partial schedule. The decision set *D* contains indices of the unscheduled activities with every predecessor being in the scheduled set. In each stage one activity from the decision set is selected with a priority rule (in case of ties the next priority rule or the smallest activity number is applied to select the activity) and scheduled at its earliest precedence, resource and workspace feasible start time. Afterwards, the selected activity is removed from the decision set and put into the scheduled set. This, in turn, may place a number of activities into the decision set, since all their predecessors are now scheduled. The algorithm terminates at the stage number $j = N$, when all activities are in the scheduled set. The advanced serial scheme can be formally specified as follows:

INITIALISATION: $j := 1 \quad S_j := \varnothing$;

WHILE $j < N$

BEGIN

COMPUTE

$$D_j := \{n = 1,...,N \mid n \notin S_j, \forall m = 1,...,M, n = Sc(m) \rightarrow Pr(m) \in S_j\}$$

$$n^* := \min_{n \in D_j} \{n \mid \theta(n) = \min_{n \in D_j} (\theta(n))\}$$

FOR $k = 1,...,K$

BEGIN

$$\overline{u}_{n^*k} := \{\overline{u} \mid \tau(\overline{u}) = \min_{\overline{u} \in \overline{U}_{n^*k}^{Sj}} (\tau(\overline{u}))\}$$

CREATE LINKS BY $\overline{u}_{n^*k}$

END

$t_{n^*} := earliest\ start\ preserving\ (2),(3),(6),(7)\ for\ \forall t \mid t_{n^*} \le t \le t_{n^*} + d_{n^*}$

$D_{j+1} := D_j \setminus n^*$

$S_{j+1} := S_j \cup n^*$

$j := j+1$

END;

STOP;

Within the presented scheme at every step $j = 1,...,N$ a decision set D_j is formed and updated according to precedence relations. Using a priority rule function $\theta(n)$, the priority values are computed for all activities from the decision set and the activity with the maximum priority value is selected. Different priority rules are admitted within this scheme.

For the prioritized activity a_{n^*} and for each its consumable resource r_k an optimum route $\overline{u}_{n^*k}$ is determined to minimize the transfer time $\tau(\overline{u}_{n^*k})$ at the set of all the possible routes $\overline{U}_{nk}^{Sj} = \left\{ \left\{ \Delta u_{nk}^{n_m} \right\}_{m=1}^{M(n,k)} \mid n_m \in S_j, m = 1,...,M(n,k) \right\}$, originating from the workspaces of the scheduled activities whose indices are already contained in the set S_j:

$$\overline{u}_{n^*k} := \left\{ \overline{u} \mid \tau(\overline{u}) = \min_{\overline{u} \in \overline{U}_{n^*k}^{Sj}} (\tau(\overline{u})) \right\} \tag{8}$$

Having got the resource route, the transfer links are created with the lags corresponding to the time delays $\tau^k(\Delta u_{n^*k}^{n_m}, i(n_m,k), i(n^*,k))$ for each portion of the delivered resource $\Delta u_{n^*k}^{n_m}$. Finally, the prioritized activity a_{n^*} is scheduled so that both precedence relations (2), resource limits (3), workspace mitigation constraints (6), and induced workflow links conditions (7) are satisfied. The decision and scheduled sets are updated properly and the method proceeds to the next step.

3.2 Priority scheduling rules

The number of priority rules proposed is relatively high. The MTS, LST, GRPW, WRUP, LFF, MSLK rules mentioned above well suit to the RCPSP problems, but fully ignoring the spatial factors unlikely they would remain workable for the considered WWCPSP statements. Once the workspace and workflow constraints have been specified, effective priority rules for the WWCPSP problem can be proposed. In order to prevent the workflow disturbance and to keep resource traffic reasonable, the rule should minimize the resource moving time. It can be reached if the resources are supplied from the nearest workspaces with a minimal transfer time according to the function (8). If the units placed in a nearby workspace are not enough for the scheduled activity a_n, then the search is propagated over distant workspaces with an expectation that the requested units can be collected from several workspaces. The transfer time can be estimated for every sort of the requested resource and for every reallocated portion. This time may have impact to earliest start of the scheduled activity. As a result, the activity may be delayed by Δd_n due to all the resource transfers. The activities having minimum delay with respect to the original duration $\Delta d_n / d_n$ should be prioritized to avoid high resource traffic. We call this priority rule by a Moving Delay Ratio (MDR) and apply it as the first priority rule invocated by the function $\theta(n)$. In case of ties, LFF or MSLK are applied as secondary rules for the function $\theta(n)$.

3.3 Resource reallocation model

First of all, the method is based on an assumption that the time transfer function can be simplified and its dependency on the amount of reallocated resource units can be represented by a separate multiplier so that

$$\tau^k(\Delta u, i', i'') = \frac{1}{s^k(\Delta u)} \cdot \rho^k(i', i''), \tag{9}$$

where the value $s^k(\Delta u)$ plays role of the speed of the resource transfer and the factor $\rho^k(i', i'')$ means the length of a traversing path from the workspace $w_{i'}$ to the workspace $w_{i''}$. The second factor can be given in a tabular form $\{\rho^k_{i',i''}\}$ providing the path lengths among all the workspace pairs. Unfortunately, the use of the tabular form looks unrealistic for large projects as it would require manual input of huge data. An analytical form based on Euclidean, Manhattan or maximum norm for the 3-dimensional vector connecting geometric centers or corners of the workspaces is more convenient for practical purposes. However, it may produce wrong estimates of the path lengths and prevent right choice of next activities when traversing the project space. As an example, the distance from one room to an adjacent room along a corridor may be the same as the distance from the room to an upper room located at the next floor. But the path lengths between the workspaces seem to be essentially different. Moreover, if the activities are prioritized so that the resources to move in nearest, quickly reachable workspaces, norm-based estimates may become error-prone.

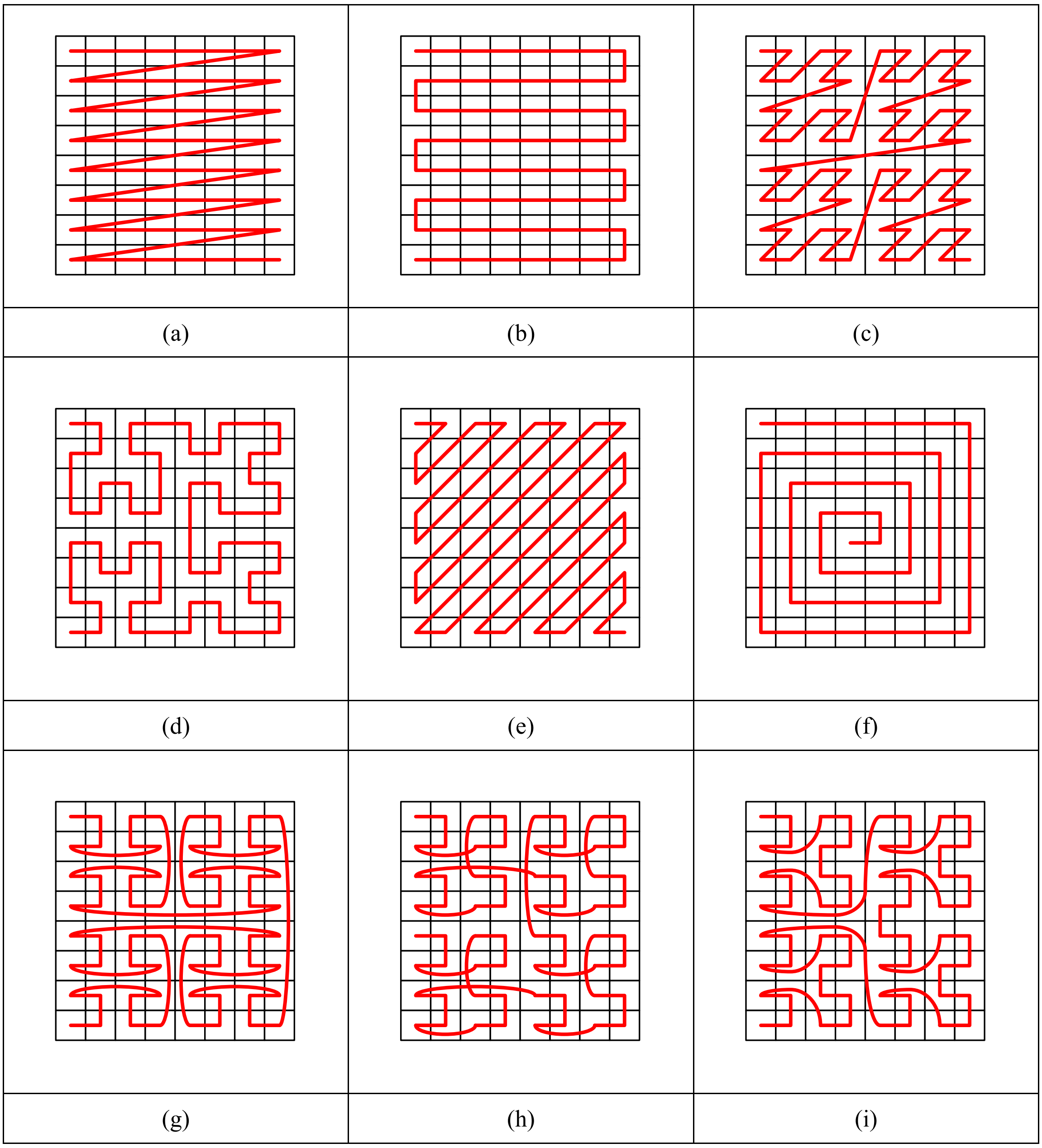


Fig. 3: Space-filling curves for the transfer time estimation.

A more promising way is to use so-called space-filling curves and to define the spatial factor by means of a distance function on these curves. The Figure 3 presents row-wise (a), prime row-wise (b), spiral-wise (f), U-wise (i) space-filling curves as well as the curves based on the well-known orderings by Morton (c), Peano-Hilbert (d), Cantor (e) and Gray (g, h). Every space-filling pattern can be generalized for the 3-dimensional case and adapted to the project space by means of altered orientations of axes of the underlying coordinate system, thereby producing 48 particular curves. The Figure 4 illustrates this variety by giving a few particular curves for 3-dimensional row-wise and Peano-Hilbert space-filling patterns. By choosing one of the patterns, adjusting its orientation in the project space and setting the cell sizes along different dimensions, the user defines a simple automatic routine for estimating resource reallocation time. If the chosen pattern and made adjustments match to a real project environment, the estimates become realistic so they can be applied when deciding on activity priorities and keeping workflows continuous.

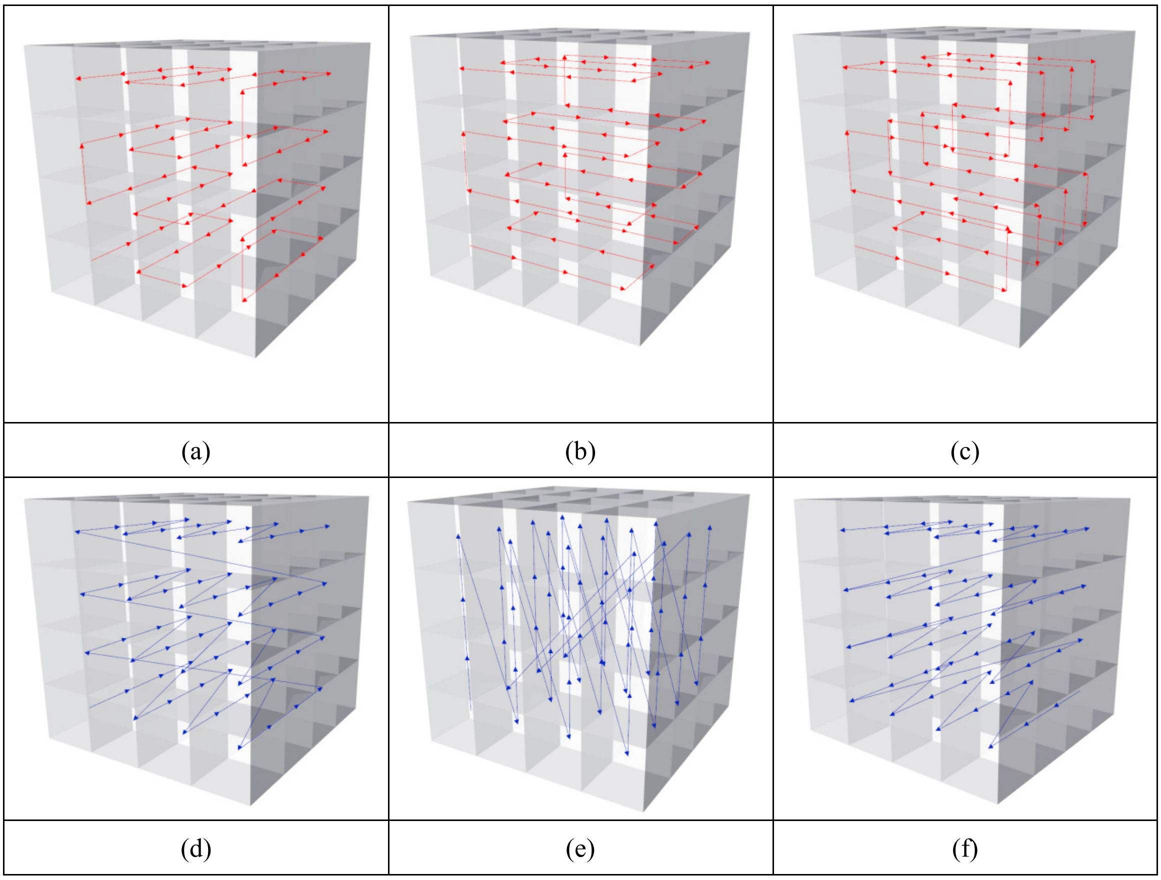
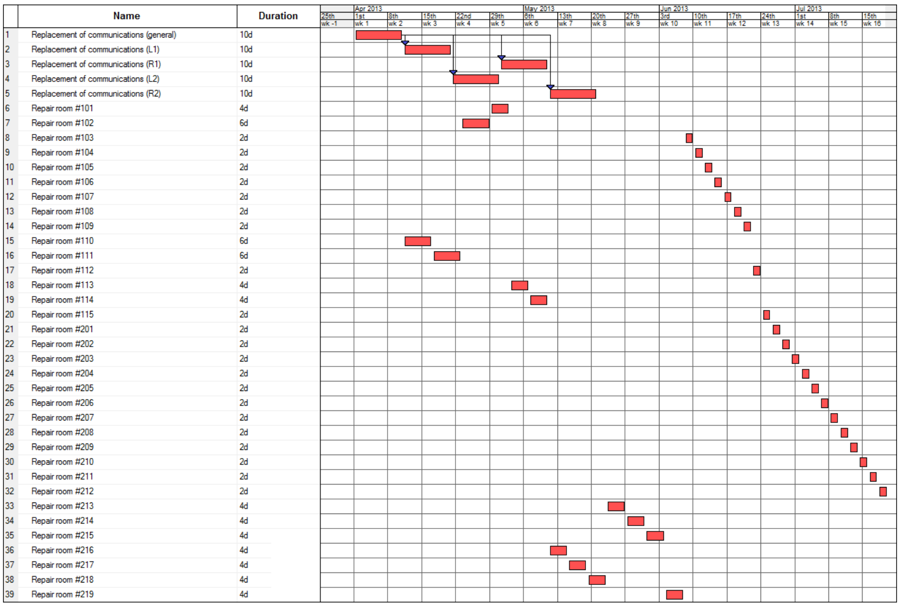


Fig. 4: Space-filling curves generalized for 3D case.

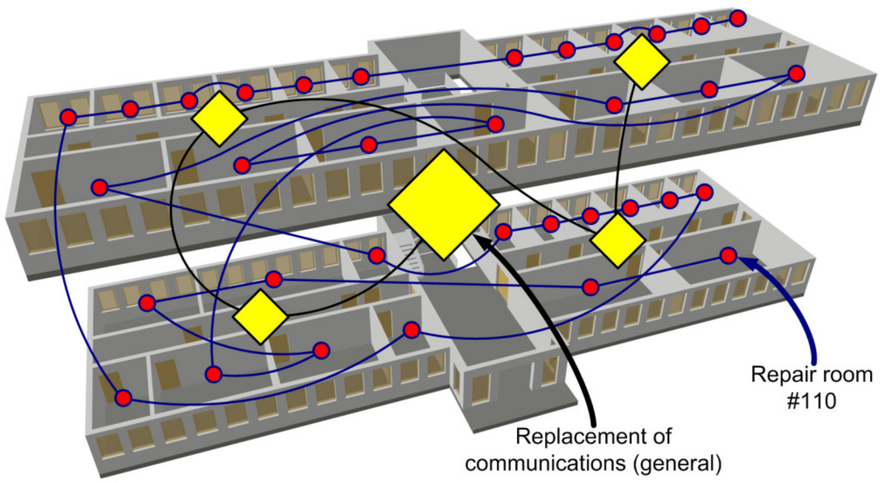
4. COMPUTATIONAL EXPERIMENTS

A simple project on refurbishing a small hotel with partial replacement of supply lines has been used for computational experiments. The hotel is a two-storeyed building having 34 rooms of three types varied in size: standard, studio and family. Time required to refurbish a room depends on its size and is 2 days for standard, 4 days for studio and 6 days for family room. Refurbishing is performed by a crew of workers room-by-room sequentially. The sequence of rooms selected for refurbishing has no matter. Replacement of supply lines is accomplished by another crew in parallel with refurbishing and subdivided into 5 stages, each of 10 days. The first stage includes works related to all the hotel building, the other 4 stages can be performed after the first one has been finished and cover only one building aisle (left and right at the first and second storey correspondingly).

Traditional planning systems usually consider workspace as a spatial resource and assign it to all the activities that should be performed in it to control its availability. As applied to the considered project, 34 spatial resources (each represents a separate room) are created. All the resources are assigned to the activity representing the first stage of supply line replacement. Resources representing rooms located at the corresponding hotel aisle are assigned to other supply line replacement activities. Only one spatial resource is assigned to the activity on refurnishing the corresponding room. Then the activities are scheduled according to a predefined priority rule, for example, latest finish time (LFT). Scheduling algorithm based on this rule is simple enough: activities with the largest duration (or latest finish time) should be scheduled first. An activity with the smallest index is selected first for scheduling among ones with equal duration. The prepared schedule is presented in the Figure 5a.



(a)



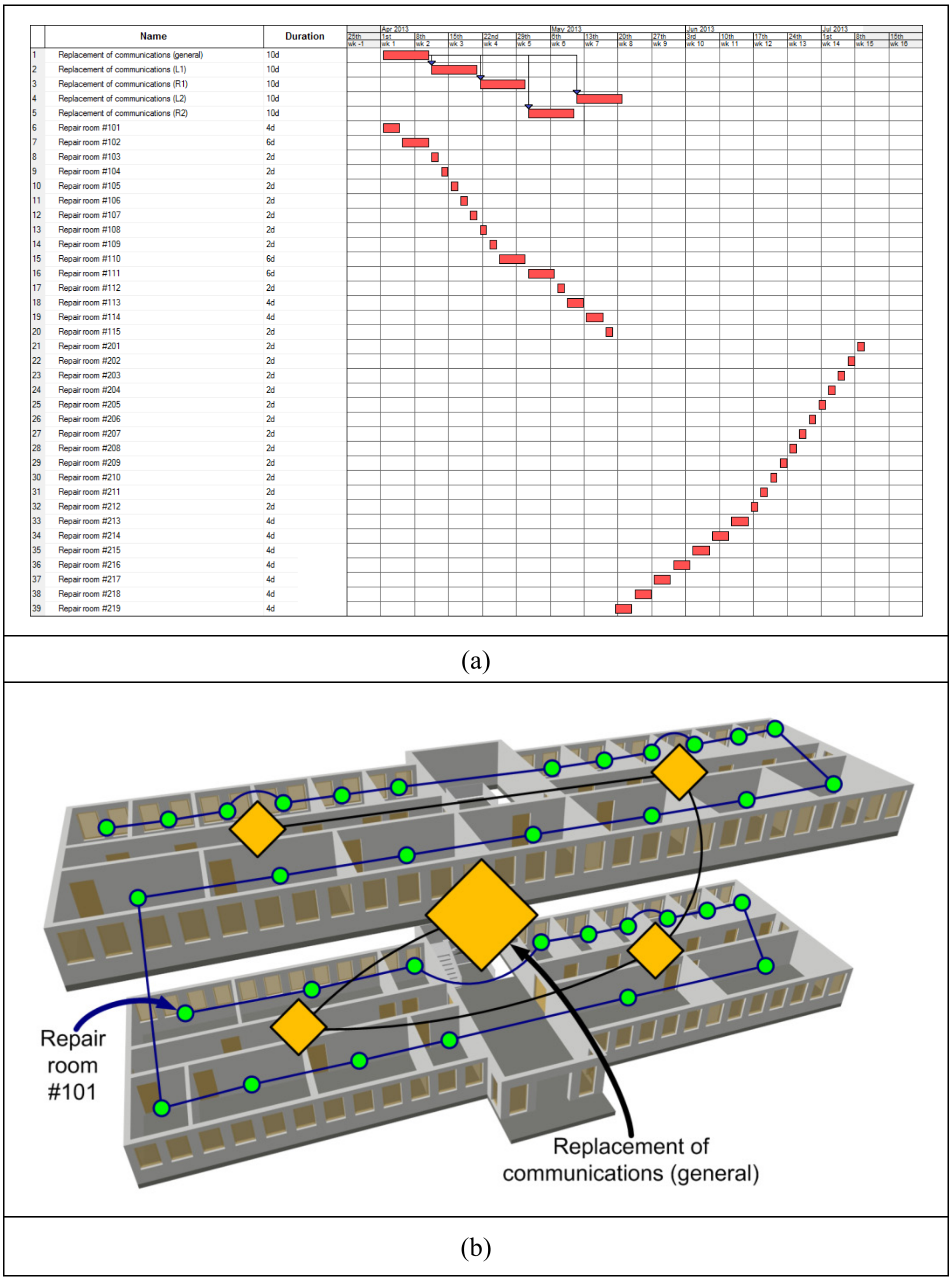
(b)

Fig. 5: Hotel refurbishing schedule prepared using the traditional RCPSP method.

Visualization of crew movement routes (see Figure 5b) demonstrates obvious shortcoming of the prepared schedule. According to it the refurbishing crew is forced to move 5 times from one aisle to another at the second storey, 3 times — from one storey to another, 3 times — from one aisle to another at the first storey. The supply line replacement crew moves 3 times from one storey to another. Such chaotic movement is inconvenient for the workers and may lead implicitly to overheads.

Conceptual difference of the proposed algorithm consists in taking into account spatial factor during scheduling procedure. In addition, the model of workspaces used in it is more accurate and flexible than reducing the workspaces to resources utilized in classical approaches. It allows loading the workspaces as much as possible.

Being applied to the discussed project, it takes into account the fact that two crews can share the same workspace at the same time if allowable by its utilization factor. One more difference of the algorithm is that the prioritization of activities depends on resource transfer time: activities with the minimum transfer time should be performed first. The time is estimated when bypassing possible routes of resource reallocation between workspaces. Activities with equal priority are scheduled according to classical approaches. The prepared schedule is presented in the Figure 6a. It is essential that the project makespan according to the schedule prepared using the proposed method is 10 days smaller than in the previous example.



(a)

(b)

Fig. 6: Hotel refurbishing schedule prepared using the WWCPSP method.

The figure 6b demonstrates that the crews should move from one storey to another only once. This is more reasonable and convenient comparing to the previous schedule. Thus, the proposed scheduling algorithm and the corresponding priority rule does not increase the total project duration and improve quality of workflow comparing to the classical approaches.

5. CONCLUSIONS

Thus, the new WWCPSP problem generalizing the classical RCPSP by taking into account spatial factor has been stated and formalized. The effective scheduling method for the problem has been proposed, investigated and approved. Like the classical approaches it tends to minimize the project makespan while satisfying timing constraint, precedence relations and not exceeding resource utilization limits. In addition, the method takes into account workspace congestion and workflow disturbance factors and allows not only to determine availability of resources to perform the project activities, but also to control overloading of workspaces and to minimize time overheads required for reallocation of resources. The conducted computational experiments showed that the method generates feasible schedules near to optimal solution at least for the low-scale benchmark problems. The reached advantages allow employing the method for the industrial needs. Such activities are planned for the next research phase.

6. REFERENCES

Ahuja H. N. (1976). Construction performance control by networks. John Wiley & Sons, New York, NY.

Boctor F. F. (1990). Some efficient multi-heuristic procedures for resource constrained project scheduling, *European journal of operational research*, No. 49, 3-13.

Bowers J. A. (1995). Criticality in resource-constrained networks, *Journal of the operational research society*, No. 46(1), 80-91.

Chavada R., Dawood N. and Kassem M. (2012). Construction workspace management: the development and application of a novel nD planning approach and tool, *Journal of Information Technology in Construction*, Vol. 17, 213-236.

Choo H. J. and Tommelein I. D. (1999). Space Scheduling Using Flow Analysis, *Proceedings IGLC-7*, 299-312.

Chua D., Yeoh K. and Song Y. (2010). Quantification of spatial temporal congestion in Four-dimensional computer-aided design, *Journal of Construction Engineering and Management*, Vol. 136, No. 6, 641-649.

David E. W. and Patterson J. H. (1975). A comparison of heuristic and optimum solutions in resource-constrained project scheduling, *Management science*, No. 21(8), 944-955.

Ellips M. and Davoud S. (2007). Classic and Heuristic Approaches in Robot Motion Planning - A Chronological Review, *Proceedings of world academy of science, engineering and technology 23*, 101-106.

Hegazy T. (1999). Optimization of resource allocation and leveling using genetic algorithms, *Journal of construction engineering and management, ASCE*, No. 125(3), 167-175.

Kolisch R., Sprechrr A. and Drexl A. (1995). Characterization and generation of a general class of resource-constrained project scheduling problems, *Management Science*, No. 41(10), 1693-1703.

Kolisch R. (1996a), Efficient priority rules for the resource-constrained project scheduling problem, *Journal of Operations Management*, No. 14, 179-192.

Kolisch R. (1996b), Serial and parallel resource-constrained project scheduling methods revisited: Theory and computation, *Journal of Operations Management*, No. 90, 320-333.

Lavalle S. M. (2006). Planning algorithms. Cambridge University Press, UK.

Semenov V. A., Kazakov K. A, and Zolotov V.A. (2011). Virtual Construction: 4D Planning and Validation, *Proceedings of the XI International Conference on Construction Applications of Virtual Reality*, 135-142.

Siddesh K Pai, Preeti Verguese and Shweta Rai (2013). Application of Line of Balance Scheduling Technique (LOBST) for a Real estate sector, *International Journal of Science, Engineering and Technology Research (IJSETR)*, Vol. 2, Is. 1, 82-95.

Thabet W. Y. and Beliveau Y. J. (1994a). Modeling Work Space to Schedule Repetitive Floors in Multistory Buildings, *Journal of Construction Engineering and Management*, No. 120(1), 96-116.

Thabet W. Y. and Beliveau Y. J. (1994b). HVLS: Horizontal and Vertical Logic Scheduling for Multistory Projects, *Journal of Construction Engineering and Management*, No. 120(4), 875-892.

Yeoh K. W. and David K. H. Chua (2012). Mitigating Workspace Congestion: A Genetic Algorithm Approach, *EPPM 2012 Conference*, 107-118.

Zouein P. P. and Tommelein I. D. (1999). Dynamic Layout Planning Using a Hybrid Incremental Solution Method, *Journal of Construction Engineering and Management*, No. 125(6), 400-408.

CONSTRUCTION PROCESS MODELLING: A CONSTRAINED GRAPHICS APPROACH VERSUS CONVENTIONAL CONSTRUCTION SIMULATION

Ian Flood & Valeh Nowrouzian
University of Florida, USA

ABSTRACT: *Effective construction project planning and control requires the development of a model of the project's construction processes. The Critical Path Method (CPM) is the most popular project modelling method in construction since it is relatively simple to use and reasonably versatile in terms of the range of processes it can represent. Several other modelling techniques have been developed over the years, each with their own advantages and disadvantages. Linear scheduling, for example, has been designed to provide highly insightful visual representations of a construction process, but unfortunately is largely incapable of representing non-repetitive construction work. Discrete-event simulation is generally agreed to be the most versatile of all modelling methods, but it lacks the simplicity in use of CPM and so has not been widely adopted in construction. A new graphical constraint-based method of modelling construction processes, Foresight, has been developed with the goal of offering the simplicity in use of CPM, the visual insight of linear scheduling, and the versatility of simulation. Earlier work has demonstrated the modelling versatility of Foresight. As part of a continuing study, this paper focuses on a comparison of the Foresight approach with discrete-event construction simulation methods, specifically Stroboscope (a derivative of CYCLONE). Foresight is shown to outperform Stroboscope in terms of the simplicity of the resultant models for a series of case studies involving a number of variants of an earthmoving operation and of a sewer tunnelling operation. A qualitative comparison of the two approaches also highlights the superior visual insight provided by Foresight over conventional simulation, an attribute essential to both the effective verification and optimization of a model.*

KEYWORDS: *Construction process, Foresight, process modeling, construction simulation, Stroboscope, model complexity, visual insight.*

1. BACKGROUND

A wide range of methods for modelling construction processes have been developed over the last 100 years. An analysis of the genealogy of these tools (Flood et al. 2006) shows that they can be divided into three main categories: the Critical Path Methods (CPM); the linear scheduling techniques; and process simulation. Most other tools are either an enhancement or an integration of these three basic classes of model. For example, 4D-CAD and nD-CAD methods (Koo & Fischer 2000; Issa et al. 2003), where one of the dimensions is time, are strictly CPM models hybridized with 3D-CAD for visualization purposes. Unfortunately, each of these three main classes of modelling is restricted in terms of its scope of application and/or usability.

First, the CPM methods (the most popular tool for planning, monitoring and control of construction processes) are well suited to modelling projects at a relatively general level of detail, but are limited in terms of the types of interactions they can consider between tasks (Harris & Ioannou 1998). Moreover, CPM models can become unduly complicated when used to model repetitive processes, and provide little understanding of the interactions between repetitive tasks. When presented in Gantt Chart format, a CPM model provides some visual insight into how a system's logic affects its performance (thus suggesting more optimal ways of executing work) but this is limited to event-based logical dependencies and their impact on time-wise performance.

Linear scheduling, on the other hand, is targeted at projects where there is repetition at a high level, such as high-rise, tunnelling, and highway construction work (see, for example, Matilla and Abraham (1998)). These models are very easy to understand and represent the system's logic and its performance within a single framework. Consequently, they provide powerful visual insight into more effective ways of executing a project. For example, they show in graphic form how the relative progress of repetitive tasks can lead to conflict, for any key variable including time and the amount of physical work completed. However, linear scheduling cannot be used to model

Citation: Flood, I. & Nowrouzian, V. (2013). Construction process modelling: a constrained graphics approach versus conventional construction simulation. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

non-repetitive work, and they include some simplistic assumptions which often make it difficult to model real-world repetitive processes. For example, velocity diagrams (a linear scheduling technique) cannot easily represent operations that follow different physical paths, such as is the case for two underground utility lines that interact at a cross-over point but otherwise follow different routes.

Finally, simulation (see, for example, Halpin and Woodhead (1976); Hajjar and AbouRizk (2002)) is very versatile in that it can in principle model any type of interaction between tasks and any type of construction process (including repetitive and non-repetitive work). However, the effort involved in defining and validating a simulation model means that in practical terms it is best suited to systems that cannot be modelled with sufficient depth and accuracy using CPM or linear scheduling. In addition, simulation models provide no visual indication of how a system's logic determines its performance. That is, the simulation diagram only shows the logic of the model and its physical resources; performance is presented in a separate output after the model has been fully developed and debugged. In other words, the logic of the model and its performance are not integral parts of a single model and therefore the dependence between performance and model logic is not directly apparent.

Most construction projects include a variety of processes some of which may be best modelled using CPM while others may be better represented by linear scheduling or simulation. However, it is not normally practical to expect planners to employ more than one modelling method to plan, monitor and control a project. In any case, using several tools that are not fully compatible makes it impossible to seek a globally optimal solution to a planning problem. On the other hand, the alternative approach of using one tool to represent all situations (which is typically CPM) compromises the ability to plan and control work optimally. Ideally, what is required is a single tool that is highly versatile in terms of the scope of construction processes it can model, provides visual insight into better ways of organizing work all aspects of work, and is easy to use. Earlier work (Flood, 2010) has proposed a new modelling paradigm, Foresight, that addresses the above issues. Foresight is being evaluated in an on-going study comparing its utility to the alternative construction process modelling techniques. This paper is concerned with part of this work, comparing Foresight to traditional construction simulation (specifically Stroboscope (Martinez, 1996)). Section 2 introduces the principles of the Foresight modelling system. Section 3 provides a case study comparing the complexity of Foresight and Stroboscope models for variants of an earthmoving operation. Section 4 provides a similar comparison for a more complicated construction process, that of a sewer tunnelling operation. Section 5 provides a qualitative comparison of Foresight and Stroboscope in terms of their utility in developing and optimizing a model.

2. FORESIGHT AND STROBOSCOPE MODELING APPROACHES

CYCLONE (Halpin and Woodhead, 1976) is the most widely published construction simulation language, and Stroboscope (Martinez, 1996) is the most advanced derivative of CYCLONE in terms of functionality, both of which are implemented using discrete-event simulation principles. This study will compare the modelling utility of Foresight with that of Stroboscope. It is assumed that the reader has a basic understanding of discrete-event simulation and of Stroboscope. Further information on Stroboscope can be found in Martinez (1996). The following provides an introduction to Foresight.

The main goals in developing the Foresight modelling language were to attain the simplicity in use of CPM, the visual insight of linear scheduling, and the modelling versatility of simulation. In addition, hierarchical structuring of a model (see for example, Huber et al. (1990) and Ceric (1994)) and interactive development of a model were identified as requisite attributes of the new approach since they facilitate model development and aid understanding of the organization and behaviour of a system. The three principle concepts of the Foresight modelling approach are as follows and illustrated in Figure 1:

1. **Attribute Space.** This is the environment within which the model of the process exists. Each dimension defining this space represents a different attribute involved in the execution of the process, such as time, cost, excavators, skilled labour, number of repetitions of an item of work, permits to perform work, and materials. The attributes that make-up this space are the resources that are used to measure performance and/or that could have a significant impact on performance.

2. **Work Units.** These are elements that represent specific items of work that need to be completed as part of the project. They are represented by a bounded region within the attribute space. A unit can represent work at a high level (such as 'Construct Structural System'), a low level (such as 'Erect Column X') or any intermediate level. Collectively, the work units must represent all work of interest but should not represent any item of work more than once.

3. **Constraints and Objectives.** Constraints define the relationships between the work units and the attribute space, either directly with the attribute space (such as constraint 'a' in Figure 1) or indirectly via relationships with other work units (such as constraints 'b', 'c', and 'd' in Figure 1). These constraints effectively define the location of the edges of the work units. A constraint can be any functional relationship between the borders of the work units and/or the space within which they exist. Practical examples include: (i) ensuring that crews at different work units maintain a safe working distance; (ii) ensuring that the demand for resources never exceeds the number available; (iii) determining the duration for a task based on the number of times it has already been repeated, and (iv) ensuring that idle time for a task is kept to a minimum. The objectives are the specific goals of the planning study, such as to maximize profits or to complete work by a deadline (such as constraint 'd' in Figure 1). Fundamentally, they are the same thing as constraints, albeit at a higher level of significance, and therefore are treated as such within the proposed modelling system.

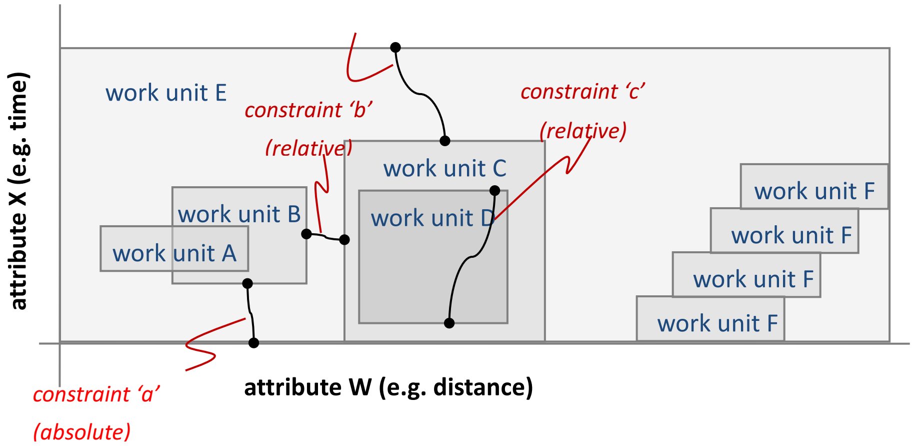


Fig. 1: Schematic of the three principle concepts of Foresight.

Note that work units can be nested within other work units (such as work unit 'D' in Figure 1 which is shown to be within work unit 'C'), or overlap with each other (such as work units 'A' and 'B'). Nesting of work units can be defined explicitly, allowing the model to be understood at different levels of abstraction, increasing its readability, reducing the likelihood of errors in the design of the model, and reducing the amount of work required to define and update a model.

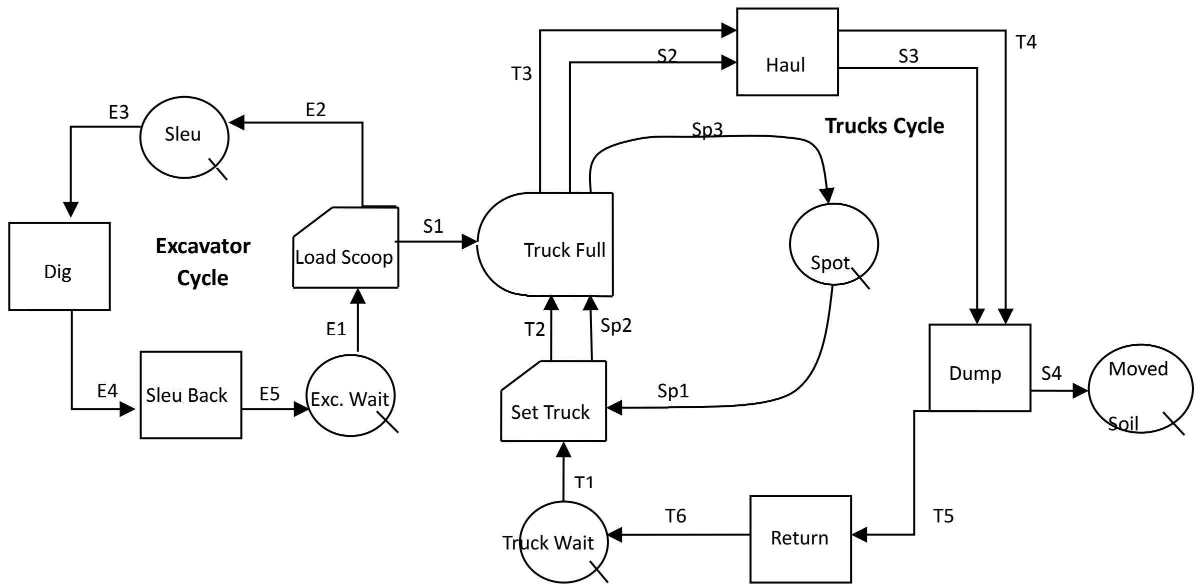
Work units can be repeated (such as work unit F in Figure 1) and can be implemented at any level within the nesting hierarchy, thus minimizing the amount of work required to define a model.

A specification of Foresight is that model development be implemented interactively. That is, the visual presentation of a model is updated and all constraints are resolved as the work units and constraints are either edited or added to the model. This way, the modeller can see immediately the impact of any changes or additions that are made. Another point to note is that these models are presented as a plot of the work units within at least two dimensions of the attribute space. This form of presentation allows the progress of work to be visualized within the model's functional structure. This is an extrapolation of the way in which linear scheduling models are presented, and has the advantage of allowing the user to visualize directly how the performance of the model is dependent on its structure. These points will be illustrated in the following case studies.

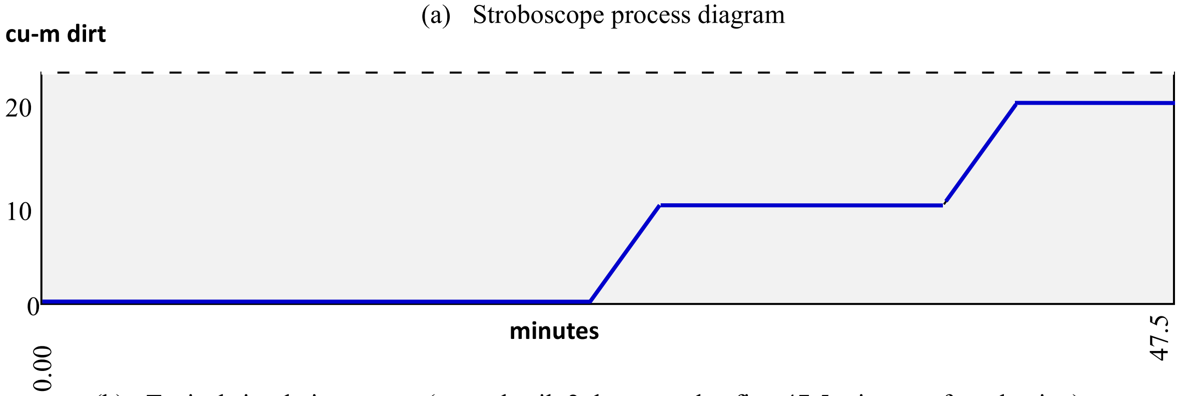
3. EARTHMOVING OPERATION

One measure of the ease of use of a modelling system is the complexity of the resultant models. In this section the complexity of a model will be measured in terms of: (i) the number of different modelling concepts that had to be employed; and (ii) the number of terms that had to be defined to complete the model. The first of these metrics provides a measure of the depth of understanding or expertise that the model builder must possess, while the second provides a measure of the effort they must input to complete the model. Modelling complexity as such was used to compare the ease-of-use of Foresight and Stroboscope for a range of variations of an excavator and distribution-truck based excavation system.

Figure 2 shows the Stroboscope representation of a simple earthmoving operation comprising a number of dump trucks of various capacity and an excavator with a 1 cu-m bucket (see Martinez, (1996)). Part (a) of this figure shows the Stroboscope diagram which is a logical representation of the processes involved in the operation, while part (b) shows the resultant time-wise output from the model measured at the dump activity for a situation where there are 2 dump trucks of 10 cu-m capacity each.



(a) Stroboscope process diagram



(b) Typical simulation output (moved soil; 2 dump trucks; first 47.5 minutes of production)

Fig. 2: Stroboscope model of an earthmoving operation (see Martinez (1996)).

Figure 3 shows the Foresight equivalent model of the same earthmoving operation. Part (a) of Figure 3 shows the hierarchical structure of the model while part (b) shows the complete model with all constraints defined, for 2 dump trucks of 10 cu-m capacity each.

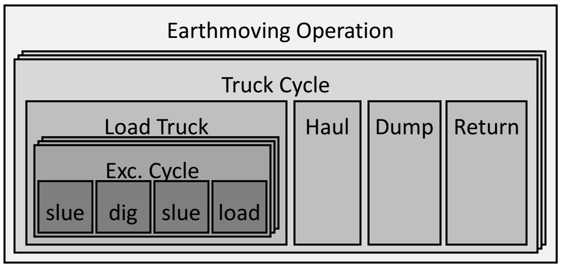
A comparison of Foresight and Stroboscope was made for the following variants of this excavation model:

1. 1 Truck (10 cu-m capacity).

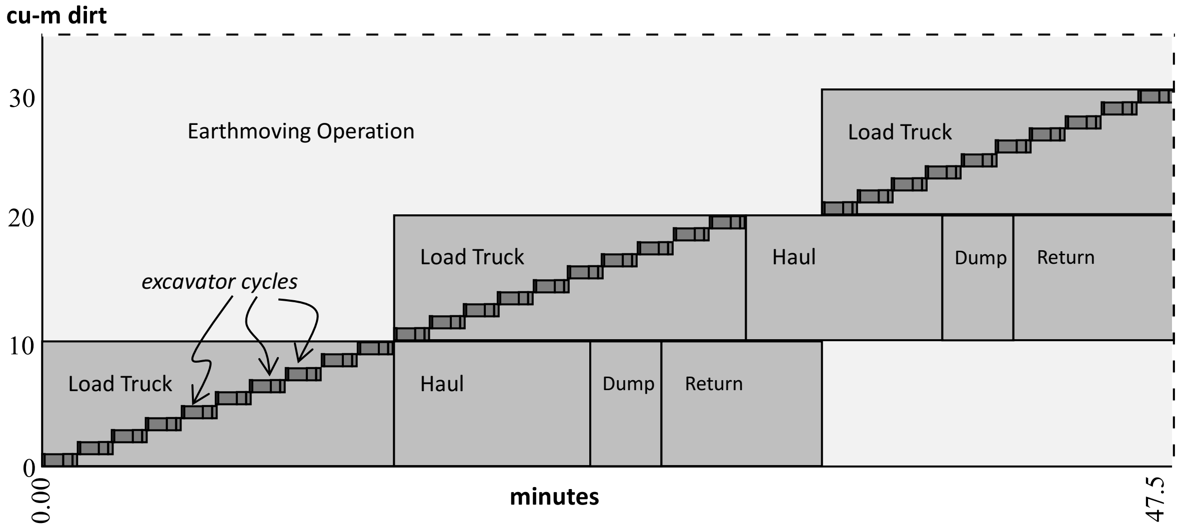
2. 2 Trucks (10 cu-m capacity) + 2 Trucks (15 cu-m capacity).

3. 3 Trucks (10 cu-m capacity) + 3 Trucks (15 cu-m capacity) + 3 Trucks (20 cu-m capacity).

All other modelling parameters were kept constant between the model variants, including the activity durations for the different truck capacities.



(a) Hierarchical model structure

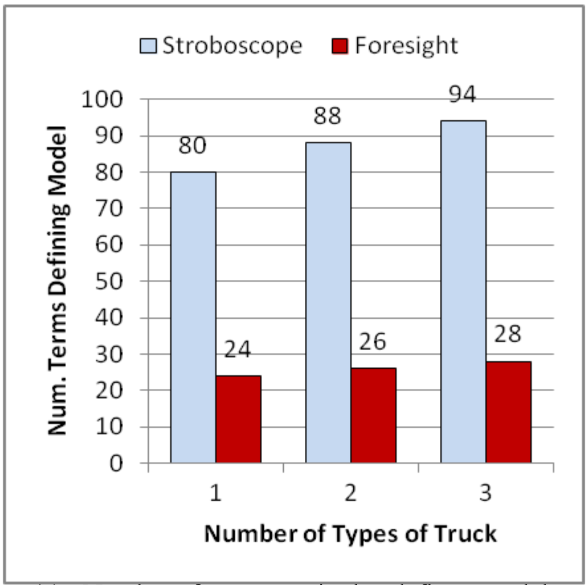


(b) Constrained model (2 dump trucks; first 47.5 minutes of production)

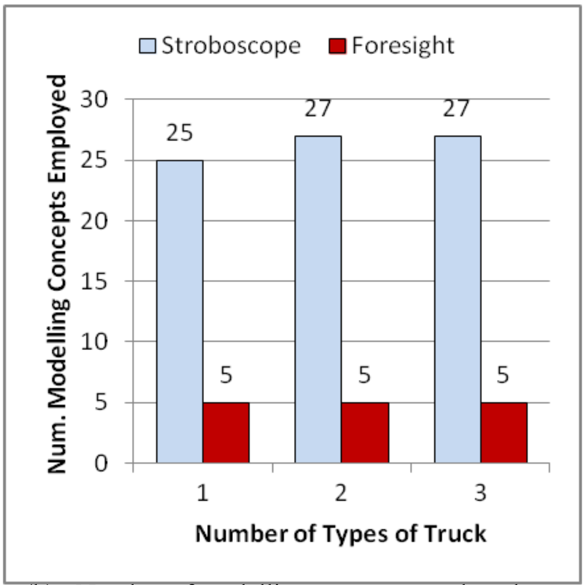
Fig. 3: Foresight model of an earthmoving operation.

Figure 4(a) shows the number of terms required to define each of the three variants of the excavation model, for both Stroboscope and Foresight. A term is taken to be any definition or parameter required to specify the structure and operation of the model. For Stroboscope, example terms are the definitions of queue nodes and activities and their linkage and durations, the definition of the excavator and trucks and their numbers and capacities, and the definitions of the amount of work to be simulated. For Foresight, example terms are the attributes such as time and soil, the work units and their constraints, and the repetition of work units (note, the amount of work to be modelled is implicitly defined by the constraints on the highest level work unit). Referring to Figure 4(a) it can be seen that the amount of information required by Foresight to define these models is about 30% of that of Stroboscope. This is significant given that the Foresight and Stroboscope models are identical in terms of the process logic represented.

Figure 4(b) makes a similar comparison but in terms of the number of concepts employed in the definition of a model – note, each concept is counted just once in this analysis no matter how many times it is employed within a model. For Foresight, there are only five concepts used to develop a model: (i) the types of attribute; (ii) the work units; (iii) the constraints defining the relative locations of the various boundaries of the work units; (iv) nesting of work units; and (v) repetition of work units. For Stroboscope, examples of concepts employed in defining a model are: queue nodes, combi activities, normal activities, consolidate functions, durations, and simulation limits. In this case, the number of concepts employed by Foresight is around 19% to 20% of that employed by Stroboscope. It could be argued that a Foresight model-builder must learn how to use the 5 base concepts to represent each logical construct in a system, such as ensuring that the excavator completes the correct number of cycles to fully load a truck. However, a Stroboscope model-builder must also learn how to configure the various Stroboscope modelling components to achieve each logical construct.



(a) Number of terms required to define a model



(b) Number of modelling concepts employed

Fig. 4: Foresight vs. Stroboscope: Complexity of variants of the earthmoving operation models

4. SEWER TUNNEL OPERATION

A second case study is presented, comparing the complexities of Foresight and Stroboscope models for a more elaborate system, that of constructing a 2 meter internal diameter sewer tunnel where tunnelling is through clay and the lining is formed from concrete ring segments. The system is described in detail in Flood (2010). Briefly, the system comprises two tunnelling crews that start in the middle and head in opposite directions. Each crew excavates clay with a pneumatic spade. Excavated material is placed in a skip mounted on light track for removal via an access shaft at the midpoint of the tunnel. Three skip loads of excavated material are required for each 1 m length of tunnel. When a 1 m length of the tunnel has been excavated, the crew brings in a set of concrete ring segments to line that section of tunnel. Once a 3 m section of the tunnel has been excavated and lined the crew lay a new section of light track. Figure 5 shows the Stroboscope equivalent of this model for 1 crew. To consider

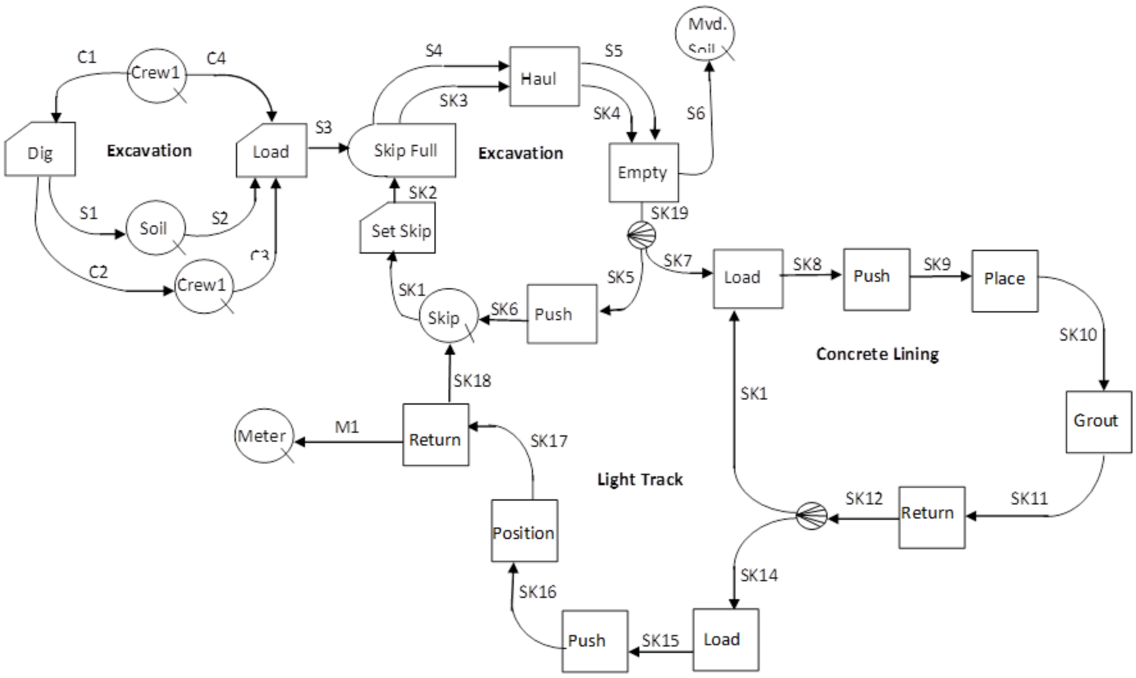
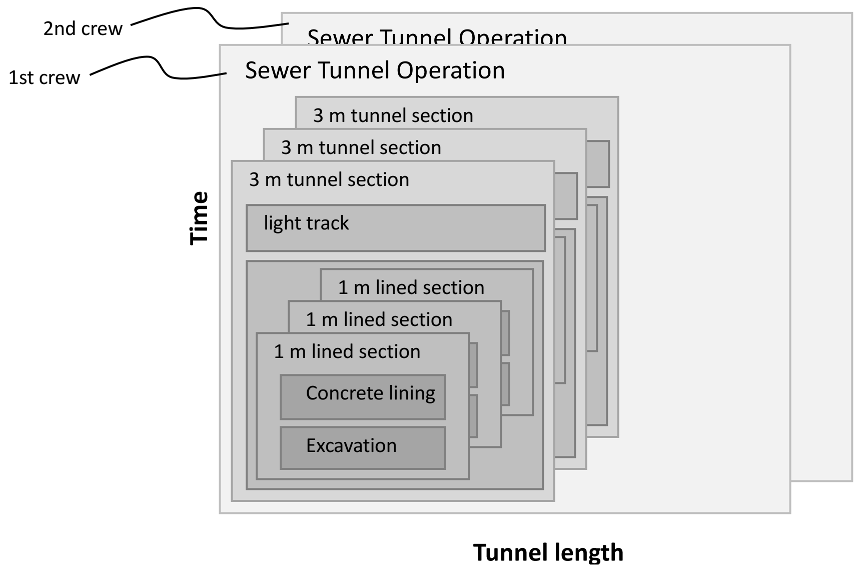


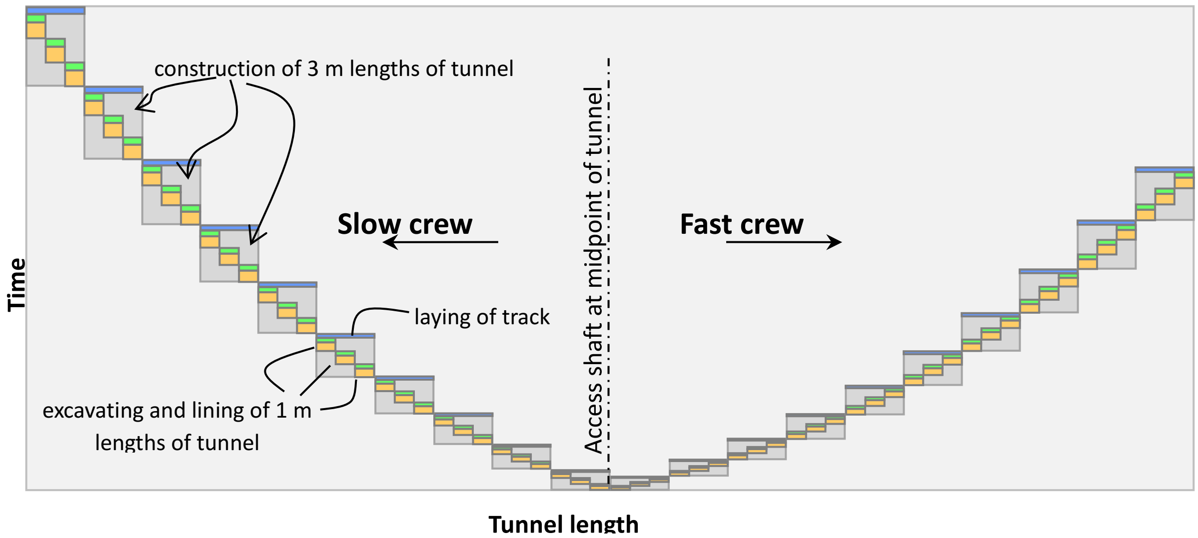
Fig. 5: Stroboscope model of a sewer tunnel operation (1 crew).

the two crews (one heading in each direction) the model as shown in Figure 5 would have to be duplicated making it effectively twice the size.

Figure 6 shows the Foresight model of the same operation. Part (a) of this figure shows the hierarchical structure of the model (for 2 crews) while part (b) shows the complete model with all constraints defined with the 2 crews heading in opposite directions. For the one crew version of this operation, Foresight required 46 terms to define the model whereas Stroboscope required 139 terms. Thus, the amount of information required by Foresight was just 33% of that of Stroboscope, a similar advantage to that realized for the earthmoving models. For the two crew versions of the model, the number of terms required to define the Foresight model increases by just 1 (totalling 47 terms), whereas the Stroboscope model requires a doubling in the number of terms (totalling 278 terms).



(a) Hierarchical model structure (2 crews).



(b) Constrained model (2 crews)

Fig. 6: Foresight model of a sewer tunnel operation (2 crews).

5. QUALITATIVE COMPARISON

The previous two sections demonstrated the advantage of Foresight over Stroboscope in terms of the relative simplicity of the resultant models. Another important advantage of Foresight over simulation is the visual insight provided by these models. This results from the fact that the logic and performance of a system are represented within a single framework in Foresight, whereas simulation techniques separate system logic from system performance. Indeed, using simulation techniques the model-builder must usually build the entire model (including defining all its parameters) before any measure of performance can be obtained. For example, the Stroboscope process diagram shown in Figure 2(a) provides no direct indication of system performance and it must be fully defined before the simulation can be executed to generate the performance results (shown in Figure 2(b)). In contrast, the Foresight model (Figure 3(b)) integrates both logic and performance within one graph, so the impact of work units and constraints on system performance is visually apparent. Moreover, the impact on performance can be seen on-the-fly as these elements are added, amended, and deleted.

These characteristics of Foresight greatly extend the utility of the approach. First, they aid model verification (debugging) by allowing the model-builder to see the impact on performance of each model edit. Second, they provide the model-builder with a visual insight that helps identify more optimal designs for a construction system. For example, by inspecting the Foresight model in Figure 6(b) it can be seen that by positioning the access shaft 3 m to the left would balance the two crews in a way that minimizes the project duration.

6. CONCLUSIONS AND FUTURE WORK

The paper has outlined a new construction modeling method, Foresight, that integrates the advantages of CPM, linear scheduling, and discrete-event simulation, along with hierarchical and interactive approaches to model development and analysis. The principles upon which Foresight is based provide it with the versatility necessary to model the broad spectrum of construction projects that until now have required the use of several different modeling tools. Compared to simulation, the resultant models are significantly less complex and require far fewer modeling concepts to be understood. In addition, Foresight models have the advantage of representing the progress of work within the model structure. This provides visual insight into how the design of a process will impact its performance, aids model verification on–the-fly, and suggests ways of optimizing project performance.

Future research will evaluate the ease with which new-users learn to develop and use Foresight models in comparison to the main alternative modeling approaches: CPM, linear scheduling, and simulation.

7. REFERENCES

Ceric, V., (1994). “Hierarchical Abilities of Diagrammatic Representations of Discrete-Event Simulation Models”, *Proceedings of the 1994 Winter Simulation Conference*, (Eds. J. D. Tew, S. Manivannan, D. A, Sadowski, and A. F. Seila), Piscataway, New Jersey, Institute of Electrical and Electronics Engineers, Inc., 589-594.

Flood, I., (2010). “Foresight: A Structured Graphical Approach to Constraint Based Project Planning”, *Proceedings of the 2nd International. Conference on Advances in System Simulation*, Simul 2010, Nice, France, IEEE, 6 pp.

Flood, I., Issa, R.R.A. and Liu, W., (2006). “A New Modeling Paradigm for Computer-Based Construction Project Planning”, *Proceedings of the Joint International Conference on Computing and Decision-Making in Civil and Building Engineering*, (Ed. Hugues Rivard), 1-11. Montreal, Canada, ASCE, 3436-3445.

Hajjar, D., and AbouRizk, S.M., (2002). “Unified Modeling Methodology for Construction Simulation”, *Journal of Construction Engineering and Management*, ASCE, 128(2), 174-185.

Halpin, D.W., and Woodhead, R.W., (1976). *Design of Construction and Process Operations*. New York, NY, John Wiley and Sons, Inc.

Harris, R.B., and Ioannou, P.G., (1998). “Scheduling Projects with Repeating Activities”, *Journal of Construction Engineering and Management*, ASCE, 124(4), 269-276.

Huber, P., Jensen, K. and Shapiro, R.M., (1990). “Hierarchies of Coloured Petri Nets”, *Proceedings of the 10th Int. Conf. on Application and Theory of Petri Nets*, (Ed. Grzegorz Rozenberg), Bonn, Germany, Springer-Verlag, 313-341.

Issa, R.A., Flood, I. and O'Brien, W., (Eds.), (2003). *4D CAD and Visualization in Construction: Developments and Applications*, Steenwijk, Netherlands, A. A. Balkema.

Koo, B., and Fischer, M., (2000). "Feasibility Study of 4D CAD in Commercial Construction", *Journal of Construction Engineering and Management,* ASCE, 126(4), 251-260.

Martinez, J.C., (1996). *STROBOSCOPE, State and Resource Based Simulation of Construction Processes,* PhD. Dissertation, University of Michigan.

Matilla, K.G., and Abraham, D.M., (1998). "Linear-Scheduling: past research efforts and future directions", *Journal of Engineering, Construction, and Architectural Management*, Blackwell Science Ltd, 5(3), 294-303.

LIVE MOBILE PANORAMIC HIGH ACCURACY AUGMENTED REALITY FOR ENGINEERING AND CONSTRUCTION

Stéphane Côté, Philippe Trudel, Marc-Antoine Desbiens, Mathieu Giguère
Bentley Systems, Québec, Canada

Rob Snyder
Bentley Systems, Lexington, KY, USA

ABSTRACT: *Augmented reality finds many potential uses in the infrastructure world. However, the work done by architects and engineers has potential impacts on people's lives. Therefore, the data they base their decisions upon must be accurate and reliable. Unfortunately, so far augmented reality has failed to provide the level of accuracy and robustness that would be required for engineering and construction work using a portable setup. Recent work has shown that panorama based augmentation can provide a level of accuracy that is higher than standard video-based augmentation methods, because of its wider field of view. In this paper, we present a live mobile augmentation method based on panoramic video. The environment is captured live using a high resolution panoramic video camera installed on top of a tripod, and positioned in the area to be augmented. The system is first initialized by the user, who aligns the 3D model of the environment with the panoramic stream. The live scene is then augmented with a 3D CAD model, the augmenting elements being properly occluded by live moving objects in the scene. To augment the scene from a different vantage point, the user grabs the tripod and carries it to the new location. During that time, the system calculates the camera position by tracking optical features identified on the panoramic video stream. When the user places the tripod back on the ground, the system automatically resumes augmentation from the new position. The system was tested in indoor and outdoor conditions. Results demonstrate high tracking accuracy, jitter free augmentation, and that the setup is sufficiently portable to be used on site.*

KEYWORDS: *Live augmented reality, accuracy, panorama, video, construction, 3D model.*

1. INTRODUCTION

Augmented reality, which consists of overlaying virtual data with the physical world, has an enormous potential in the AEC world. By aligning model data with reality, AR could enable a wide range of potentially very useful applications including: building site monitoring & planning, asset identification and query, systems monitoring, remote site work planning, surveying, safety warning systems, etc. Since these involve assets of the built environment as well as virtual data related with those assets, AEC tasks are actually ideal candidates for the implementation of AR applications.

Decisions taken by architects, engineers and builders have a direct impact on public safety. They must therefore be supported by accurate and reliable data. Augmented reality applications in the AEC world would therefore need to be very accurate. Unfortunately, while approximate, low accuracy augmentations are easy to obtain, accurate AR is very hard to achieve.

For a long time, the main difficulty with augmented reality has been (and still is) registration: the capacity to align properly the 3D model and data with the corresponding physical objects. That capacity is extremely important: if an engineer uses an AR app on site to "click" on a valve box cover to query its maintenance information, he most likely wants information about that specific box cover, and not the one located 30 cm next to it. In the AEC world, inaccurate AR applications could lead to incorrect interpretations and therefore bad decisions.

For accurate AR to be possible, one must know the exact position and orientation (the "pose") of the camera. While an approximate camera pose can be obtained relatively easily using basic and inexpensive sensors generally available on tablets and smart phones (GPS, orientation sensor, and accelerometer), an accurate pose is extremely difficult to obtain without a complex an expensive setup. Poirier (2011) estimated that to augment an object located 2 meters away with a 1-pixel accuracy using a 640 × 480 pixel resolution camera, the exact camera pose needs to

Citation: Côté, S., Trudel, P., Desbiens, M-. A., Giguère, M. & Snyder, R. (2013). Live mobile panoramic high accuracy augmented reality for engineering and construction. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

be known within 0.09 degree for orientation and 3.5 mm for position. Such a level of accuracy can be obtained using a complex setup (for example: limited range tracking systems used for virtual reality), which unfortunately is incompatible with outdoor mobile augmentation.

Considering the various limitations of pose measurement hardware, the problem of image-based tracking has received a lot of attention. By identifying and matching features that appear on sequential frames of a live video stream and matching those with a 3D model of the environment, it is possible to calculate the camera pose. Such methods have now reached a point where they can be used to capture limited size environments and track a moving camera in real time. However, such methods are still far from perfect. One of the main limitations of those techniques is the fact that most cameras have a limited field of view – typically about 60 x 30 degrees, up to 120 degrees diagonally. Since image-based tracking is dependent on tracking identified features, tracking will only be possible if such features exist in the first place. Although visual features are omnipresent in our world, features are not always suitable, or not always present in a sufficient number for tracking, for instance: moving targets (vehicles, tree leaves blown by wind) or repetitive patterns (brick wall), etc. Sometimes features may just be undetectable: low contrast areas (shadow), uniform surfaces (painted walls, sky), etc. Naturally, the use of narrow field of view cameras makes the situation even worse, as it increases the chances of capturing zones of the physical environment that are unsuitable for tracking. In addition, such cameras limit the capacity to view features over long distances, which limits the accuracy of the resulting pose (Lemaire and Lacroix, 2007). Another problem is related with user's movements: A tablet is held in user's hands. It is therefore subjected to constant movement – making accurate tracking even more challenging to achieve in real time.

Over the past few years, work has been done on the augmentation of static panoramic images (Côté 2011a, 2011b, 2012; Wither et al., 2011; Hill et al., 2011). Static images can be augmented more easily than video: since the camera position is fixed, they require no position tracking. In addition, a 3D model can be aligned more accurately with panoramic images because the alignment can be done on features distributed around the 360^{o} field of view, increasing the chance of capturing areas that are suitable for tracking (Argyros et al., 2001). Unfortunately, static images become out of date from the moment they are captured. Moreover, because they are static, the augmentation of such images can incorporate no dynamic event. What would be nice would be to develop an augmentation method that shares the advantages of panoramic images (accurate and stable augmentation) with those of live cameras (real time augmentation).

In this paper, we propose an augmentation system that circumvents the limitations of standard aperture cameras and of static panoramic images by providing a stable and accurate, yet mobile and live augmentation experience. We propose an augmentation system based on panoramic video streams. The system augments a live panoramic scene in real time. Features identified on sequential frames of a panoramic stream are tracked as the camera moves. The location of each feature in the panoramic stream enables the system to calculate the camera position, as it is being moved in the environment. We implemented and tested our method in a real environment, both indoor and outdoor. Our qualitative results confirm that our system can track the camera position in real time, and provides stable augmentations that show no jitter. We envision that such a system could be used to implement high accuracy augmentation systems.

2. RELATED WORK

Live augmented reality has been invested by a large number of investigators. However, only a few of them worked with panoramic imagery. Panoramic tracking has been studied by Jogan and Leonardis (2000) who present a method for robust localization using panoramic images in a pre-learned environment, and Fiala and Basu (2004) who show a robot navigation system based on panoramic landmark vertex and line tracking. Langlotz et al. (2011) built a system where 3 DOF camera tracking can be obtained using a pre-registered panoramic environment.

Static panoramic augmented environment have been described by Côté (2011a, 2011b, 2012) and Wither et al., (2011). Langlotz et al. (2011) demonstrated live augmentation of pre-recorded video from a fixed position. Hill et al. (2011) showed a mirror world augmentation system in which pre-captured panoramic images of the environment were augmented when the user stood approximately at their image capture position. In these systems, static panoramic images were used. Those offer the advantage of providing precise augmentation (since no camera tracking is required). Augmentation based on panoramic media also has the potential of being much more accurate because of the numerous points of control located all around the camera that can be tracked over long distances (Lemaire and Lacroix, 2007) and because of the increased chance of capturing areas of the environment that are suitable for tracking (Wither et al., 2011).

3. METHOD

3.1 Data

Our panorama-based augmentation system requires 3 types of data: live panoramic video stream, tracking model and augmentation model.

3.1.1 Live panoramic video stream

The live panoramic video stream is used as a representation of the physical world. It is displayed on screen with the overlaid augmentation. The streams were captured live using a Ladybug 3 panoramic camera from Point Grey Research (see Fig. 1(A)). The camera was connected to a laptop computer (see Fig. 1(B)), used as a "server", through an IEEE 1394b FireWire 800 connection allowing 800 Mbps of data transfer. The video streams received from each of the 5 individual camera sensors were processed in real time into a single stitched and color corrected equirectangular panoramic stream. The live stitching and color processing program was developed in C++ using the Ladybug SDK. On a quad core laptop, our panorama processing program could achieve 15 FPS for panorama resolution of 3500 × 1750 pixels. The panoramic frames were then transferred live to a second laptop (see Fig. 1(C)), used as a "client" that processed the stream and displayed the augmentation, via a 1 Gbps Ethernet connection, at a rate of about 5 images per second (uncompressed). We used 2 laptops because the capture and processing of live panoramic video occupied the first laptop full time, leaving no processing time available for tracking and augmentation.

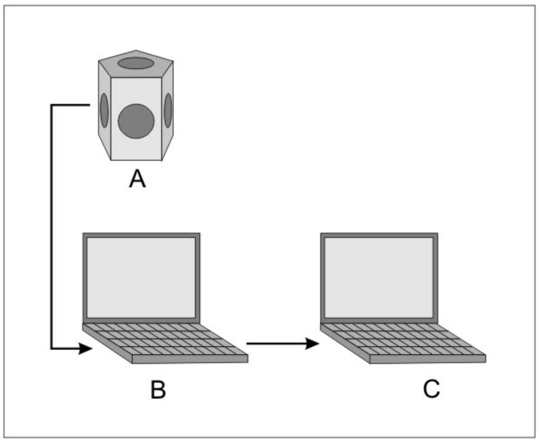


Fig. 1: Hardware setup used for the experiment. A panoramic camera (A) is connected to a first (server) laptop (B) via a Firewire 800 connection. Laptop (B) is connected to a second (client) laptop (C) via a 1 Gbps Ethernet connection.

3.1.2 Tracking model

The tracking model is used as a basis for camera tracking. In this experiment, the tracking algorithm relies on a very simple tracking model obtained from a CAD model of the test area. It is composed of flat or poorly detailed surfaces that represent building walls, floors, and road surface. A tracking model containing only few details helps keep the tracking process fast.

3.1.3 Augmentation model

The augmentation model contains the 3D data to use for augmentation. It could contain, for instance, elements that represent hidden assets such as pipes, cables, structure, etc. The tracking and augmentation models are aligned and share the same georeference. In our experiment, the augmentation model is a detailed CAD model of the test area. Initially stored in DGN format, it was exported to our augmentation application that is based on Ogre 3D. The augmentation model is kept invisible in the augmented view until augmentation is required by the user.

3.2 Video augmentation

3.2.1 Initialization

The first part of the augmentation session is an initialization phase, in which the tracking model is aligned with the first frame of the panoramic stream. This step is required once at the beginning of the augmentation session, or when the system has lost track of the camera position. Although that step could be made automatic, in our system it is achieved manually. The camera is installed on a tripod at a fixed location, the augmentation application is loaded, and the panoramic video stream displayed on the client laptop. The camera's approximate position is also located using a GPS or manually selected on a map by the user. The georeferenced 3D tracking model is then displayed on screen overlaid to the panoramic stream, at approximately the same location (see Figure 2, left). The user has then the possibility to rotate the model, to roughly align model features with corresponding image features (e.g. building vertices). Then, he enters a set of correspondences, clicking on a model feature first, then clicking on the corresponding image feature. A minimum of 4 correspondences is required, while 7 or more, well distributed around the camera, is ideal. The correspondences are then used to calculate the camera pose with respect to the tracking model using the method proposed in (Poirier, 2011). The resulting pose is then used to accurately align the tracking model to the panoramic image (see Fig. 2, right). It takes approximately 30 seconds to 1 minute for a trained user to find and select the required correspondences. Pose calculation time is less than 1 sec.

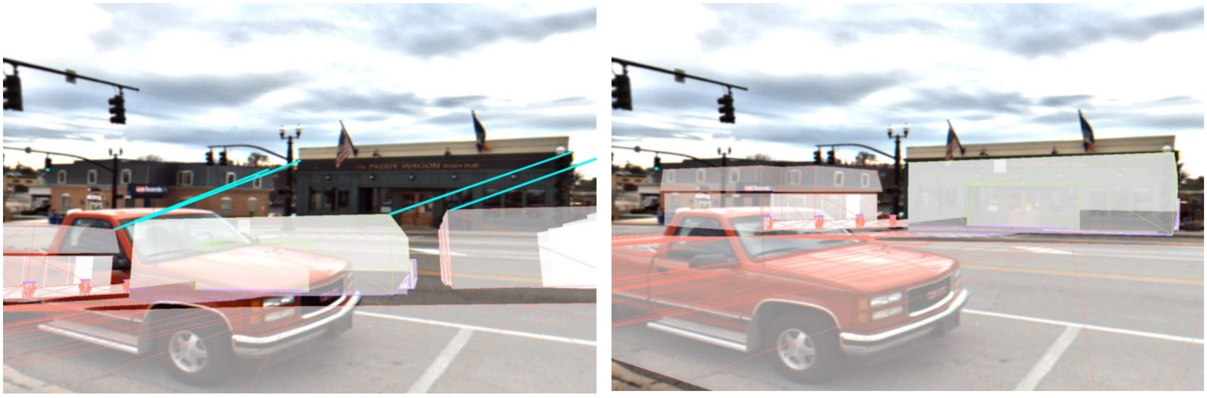


Fig. 2: Initialization process. Left: Correspondences selected by user. Right: The pose calculated from those correspondences is used to align the panorama and the tracking model.

3.2.2 Tracking

Once the initial camera position was obtained through initialization, the live camera pose must be obtained as it is being moved in the environment. That can be achieved through image tracking. We proposed and implemented a very basic image tracking algorithm: while the camera is still at its initial position, SURF features are extracted from a first frame of the panoramic stream using SURF GPU implemented on OpenCV 2.4. Those features are then projected onto the 3D tracking model from the camera position obtained through initialization. The projected location of each feature is considered as being the most likely 3D location of those image features in the physical world. A second frame of the video stream is then analyzed: SURF features are first identified, then matched with those of the first image. Only the best matches are used. The new camera pose is then calculated using the same method used in the initialization (Poirier 2011), but this time the correspondences are generated automatically based on those matches. Features captured on moving targets, or badly matched features are identified using their reprojection error, and eliminated from the pose calculation. Each feature of the second frame is then associated with a 3D position via projection, and the process restarts for a third frame. Keyframes were used to minimize drift. The algorithm used is very simple, but sufficient for us to prove the concept of panoramic tracking and augmentation.

3.2.3 Augmentation

In our current prototype, augmentation is achieved through a virtual excavation feature that lets the user see through walls, floor and ceiling. The augmentation technique is similar to the one described by (Schall *et al.*, 2010; Côté, 2011b) for augmenting subsurface utilities. In these projects, a virtual excavation is drawn on the surface of the road, revealing hidden infrastructure (see Fig. 3). The technique basically consists of creating a virtual hole in an object, by clipping all but some of the elements composing it. In this project, we used the same technique but applied it on walls, floors, and ceilings.

3.3 Use of the system

In a typical use of the system, the camera is placed on a tripod at a fixed position, and the system is initialized by the user. The camera is then carried to the first augmentation location. As it is being moved, the system tracks the camera location in real time. When the user puts the camera and its tripod back on the ground, the system knows the location of the camera, and augmentation can start right away, without the need of a new initialization step. Once the task that required augmentation from that location is complete, the user can then move the camera somewhere else and augment the world from that new location. Although the system can track the camera and augment the scene at the same time, the tracking feature can be stopped during the augmentation if the camera remains at a fixed position – that leaves more CPU power available to the augmentation application, and avoids any potential tracking error due to occlusion or some other dynamic event. The whole augmentation system introduced a lag in the video steam. Out tests revealed that on average, the augmentation was displayed about 1 to 1.5 seconds after the live events occurred.

Fig. 3: Virtual excavation for subsurface utilities as shown in (Côté, 2011b).

4. RESULTS

4.1 Improvements made to the model

We tested our method around and inside the Paddy Wagon Irish Pub located in Richmond, Kentucky, USA (see Fig. 4, left). We chose that site because we also had a detailed CAD model (BIM) of that building (Fig. 4, right), created by *McKay Snyder Architects, James McKay, Architect*, using MicroStation® and had permission to use it given by the building owner. Both our tracking and augmentation models are based on that model. The tracking model is a simplified version of the original CAD model, while the augmentation model contains only some of the invisible elements of the CAD model (structure, pipes, etc.).

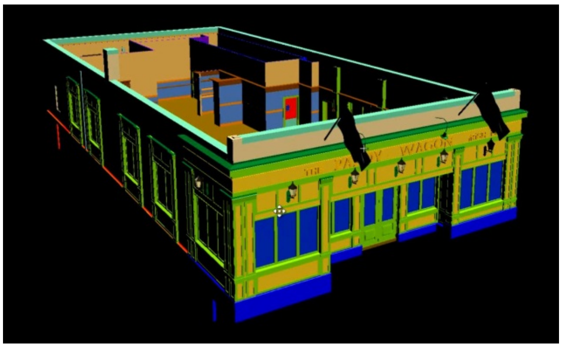


Fig. 4: The test site (left). The detailed 3D CAD model of the pub (right).

Initial tracking tests using pre-recorded video showed a low quality tracking, characterized by drifting augmentation as the camera was being moved, both indoor and outdoor. Our investigation with the outdoor scene revealed that the CAD model did not cover enough of the scene surrounding the camera - we would have needed a model for many of the neighbor buildings to enable better tracking. Indoor tracking was also very deficient, and a close examination of the model and captured panoramic videos revealed several differences between the model and the actual building. Those differences could have explained the tracking difficulties we experienced. We realized we needed to make some corrections to the design model to account for changes that were made during construction.

We therefore acquired a detailed point cloud of the area using a Leica C10 scanner. A total of 25 high density scans were completed indoor and outdoor the pub, and merged together into a point cloud containing over 750 million points (see Fig. 5). The point cloud was used to create a block model of the surrounding buildings and a basic surface model of the road surface. The superposition of the 3D model and the point cloud revealed major differences between the 2 (see Fig. 6). For instance, it turned out that the outer walls of the building do not represent a perfect rectangle, the building being slightly “skewed”. The actual differences between the model outer walls and the actual physical wall were, in some areas, as large as 8.2 cm. That difference could explain some of the augmentation discrepancies we had observed. The point cloud was therefore used to fine tune the indoor model to fit with the actual physical walls and bar structure. It was also used to add new buildings and road surface to the outdoor model to enable more stable outdoor tracking.

Fig. 5: Point cloud acquired in the test area. Neighbor buildings (top left); Close-up of façade (top right). Interior (bottom).

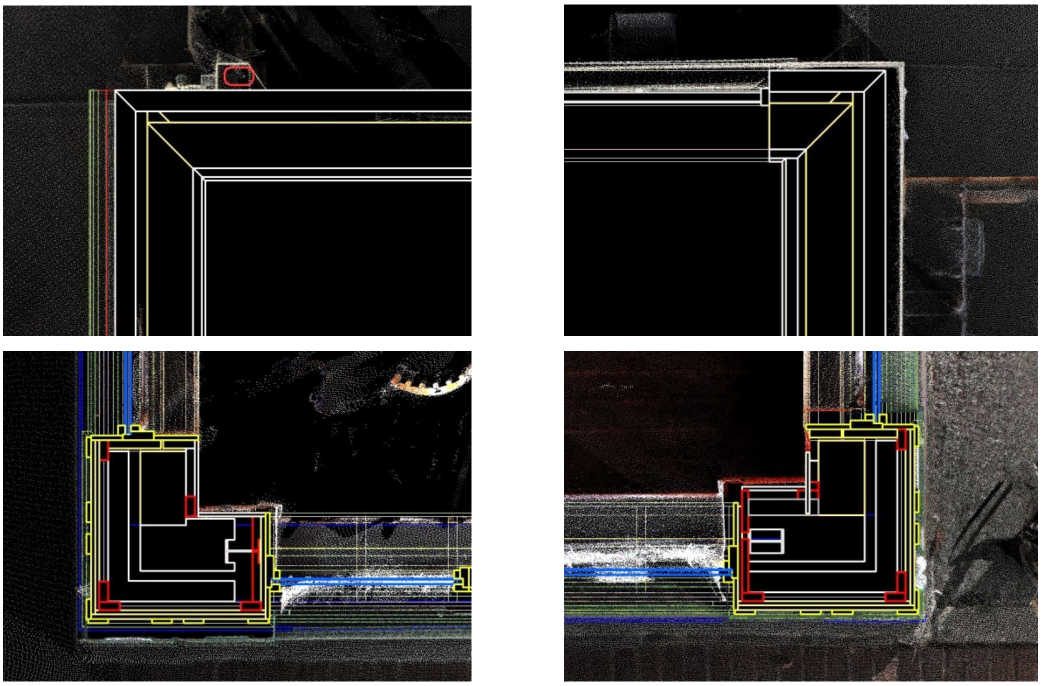


Fig. 6: Detailed view of the 4 corners of the building, in a top view, showing the difference between the model and the point cloud. Differences observed in the top right (8.2 cm) and bottom left corners (7.6 cm) cannot be fixed by model rotation or translation.

4.2 Experimental tests

4.2.1 Outdoor tracking and augmentation

The method was tested on site using 2 quad core Lenovo W520 laptops equipped with 12 Gb or RAM, and installed on top of each other on a harness worn by the tester (see Fig. 7). The panoramic camera was installed on top of a tripod and transported around the building. Although the whole setup could be carried by one user, in practice it was much easier when assisted by another user.

Fig. 7: Setup for carrying the computers and camera on site.

Results for basic camera tracking were excellent: an outdoor test where the camera was moved and rotated like a reversed pendulum showed no jitter and only a small (not quantified) amount of drift (see Fig. 8). The model remained well attached to the physical world during camera movement. We could achieve a tracking rate of 2-3 fps while moving the camera around the building. We also tested augmentation quality: on the opposite side of the building, we displayed a virtual excavation on the wall surface, that reveals model elements located inside the wall, as well as other objects located inside the pub model (see Fig. 9). The excavation could be moved freely, live, along the wall surface.

The augmentation being displayed on top of the live video stream, appeared on top of everything, even objects and people located between the camera and the wall being augmented. To avoid that undesired effect, we implemented a basic occlusion detection algorithm based on object movement. It allowed the superposition of moving objects on top of the augmentation. This way, a user can point at and draw the location of hidden pipes, as his own image is not occluded by the augmentation (see Fig. 10).

Fig. 8: Two frames extracted from the camera rotation experiment. Tracking produced no augmentation jitter, but a small amount drift accumulates over time (see rightmost part of right image).

Fig. 9: Two frames extracted from the wall augmentation experiment. Virtual excavation reveals pipes hidden inside the wall and other elements inside the pub.

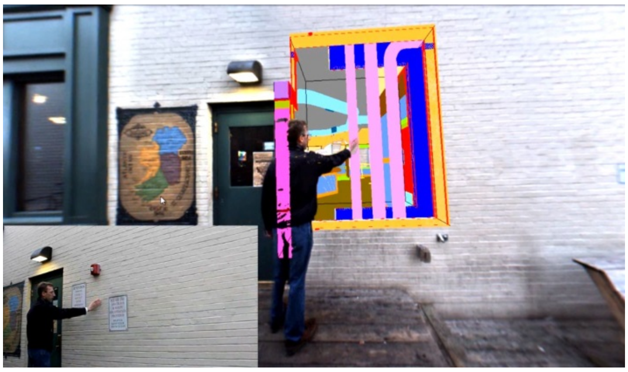


Fig. 10: Dynamic occlusion detection, based on user's movements, allows proper occlusion between user and augmentation.

4.2.2 Indoor tracking and augmentation

Inside the pub, the panoramic camera was installed on top of a tripod and a dolly, for smooth movement. The pub interior is exceptionally rich in features: wall decoration, tables, bar, bottles, etc. (see Fig. 11). Therefore, the tracking was exceptionally stable. Results from our indoor tracking experiment showed very stable tracking, without jitter, for both camera translation and rotation (see Fig. 12).

Although the model was carefully manually aligned with the panorama at the beginning of the augmentation session, we observed an increasing offset between the panoramic stream and the model. The exact origin of that drift is unknown, but we presume it is related with the tracking technique. It will be the subject of a future investigation.

Fig. 11: Indoor environment.

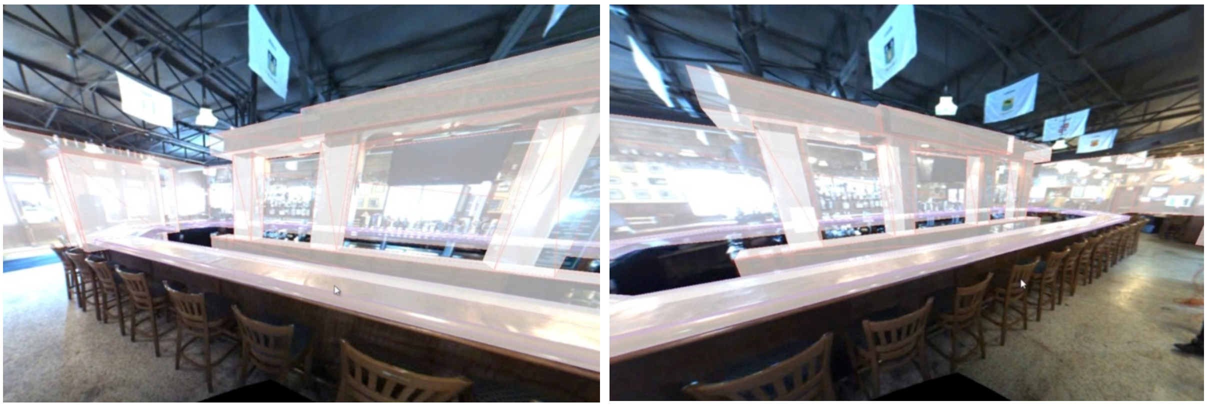


Fig. 12: Two frames extracted from our indoor tracking experiment.

5. CONCLUSION & FUTURE WORK

Our experiment showed that it is possible to obtain accurate and live augmentation in a building environment, both outdoor and indoor, using a panoramic video camera. Our results showed a stable tracking, probably because of the panoramic camera's large field of view that increases the chance of capturing areas suitable for tracking. The experiment also helped us identify the conditions that make such a stable tracking possible. In particular, our results highlighted the importance of having an accurate and detailed model of the building environment.

Our results open the door to future augmented reality applications where high accuracy is required. They also highlight the importance of further studying some aspects of panorama-based augmentation. Future research efforts could be put on:

- Minimizing the lag between live events and augmented display. This could be achieved for instance by using only one, faster computer and improving parallelism between processes.
- Improving the tracking algorithm, which currently accumulates drift and is too slow on large images.
- Obtaining good tracking without requiring a laser-based model.
- Detecting camera movement and starting the tracking feature automatically.

6. ACKNOWLEDGEMENTS

Many thanks to NSERC for financial support via the Industrial Undergraduate Student Research Award program.

7. REFERENCES

Argyros A.A., Bekris K.E. and Orphanoudakis S.C., 2001. Robot Homing based on Corner Tracking in a Sequence of Panoramic Images. In Proceedings of the CVPR 2001 conference.

Côté S. (2011a). Augmented reality for infrastructure: a first step. Published electronically on *BE Communities*.

Côté S. (2011b). Augmented reality for underground infrastructure: the problem of spatial perception. Published electronically on *BE Communities*.

Côté S. (2012). Augmented reality for building construction and maintenance: augmenting with 2D drawings. Published electronically on *BE Communities*.

Fiala M. and Basu A., 2004. Robot Navigation Using Panoramic Landmark Tracking. *Pattern Recognition*, Vol. 37 No. 11, Nov 2004.

Hill A., Barba E., MacIntyre B., Gandy M., Davidson B. (2011). Mirror Worlds: Experimenting with Heterogeneous AR. 2011 International Symposium on Ubiquitous Virtual Reality, Jeju-si, Republic of Korea.

Jogan M. and Leonardis A., 2000. Robust Localization Using Panoramic View-Based Recognition. ICPR '00 Proceedings of the International Conference on Pattern Recognition.

Langlotz T., Degendorfer C., Mulloni A., Schall G., Reitmayr G., Schmalstieg D., 2011. Robust detection and tracking of annotations for outdoor augmented reality browsing. http://dx.doi.org/10.1016/j.cag.2011.04.004

Lemaire T. and Lacroix S. (2007). SLAM with panoramic vision, *Journal of Field Robotics*, Vol. 24.

Poirier S. (2011). Estimation de pose omnidirectionnelle dans un contexte de réalité augmentée. M.Sc. Thesis, Université Laval, 2011.

Schall G., Junghanns S. and Schmalstieg D. (2010). VIDENTE - 3D Visualization of Underground Infrastructure using Handheld Augmented Reality, in GeoHydroinformatics: Integrating GIS and Water Engineering *(CRC press)*.

Wither J., Tsai W-T., Azuma R., 2011. Indirect augmented reality. *Computers & Graphics* 35, 810–822.

VISION-BASED FIELD INSPECTION OF CONCRETE REINFORCING BARS

Kevin Han, JunYoung Gwak & Mani Golparvar-Fard
University of Illinois at Urbana-Champaign, USA

Kamel Saidi, Geraldine Cheok, Marek Franaszek & Robert Lipman
The National Institute of Standards and Technology (NIST), USA

ABSTRACT: *Concrete reinforcing bars should be accurately placed in the positions shown on the construction drawings, adequately tied and supported before concrete is placed. These elements should be further secured against displacements within the tolerances recommended by project specifications. Ensuring compliance with contract documents and the building code applicable to the project under construction requires photographic documentation and close visual examination by field inspectors. Although inspection procedures are repetitive for every jobsite, the manual inspection methods are time-consuming and non-systematic. Moreover, the current practice of field inspectors walking into rebar cages and footings for close assessments can be a potential safety hazard on jobsites and can damage the integrity of the structure. To minimize the challenges of the current practice, this paper proposes a computer vision-based method for field inspection. In the proposed method, a field inspector can carefully walk around a rebar cage and take a complete collection of images from the underlying structure. Using a vision-based 3D reconstruction pipeline of Structure-from-Motion and Multi-view Stereo algorithms, a dense 3D point cloud model will be generated. Using an algorithm that maps and generates a density histogram of points, the locations and configuration of the rebars are identified. Finally, the spacings between rebars are calculated for field inspection. Experimental results on data collection, analysis, and visualization components of the proposed rebar inspection method is presented. These results show the promise of applying this low-cost approach in practice.*

KEYWORDS: *Rebar mapping, field inspection, vision-based 3D reconstruction, concrete placement*

1. INTRODUCTION

To ensure compliance with contract documents and building codes, inspection of concrete reinforcing bars (rebars) prior to pouring concrete is required for every concrete structure. These elements should be accurately placed in the positions shown on the construction drawings and secured before concrete is placed. Inspection of rebars is largely done by visual examination of the layout pattern, of measuring the spacing, and of counting rebars (CRSI 2011). Considering the large size and the significant number of concrete placements for every project, this visual inspection - which is manually conducted by field inspectors - can be very time-consuming and inconsistent. In the current practice, a field inspector with a measuring tape walks around a rebar structure and often times pictures are taken to create a visual record of the as-built status. When measuring and counting rebars far away from the inspector, the numbers may be inaccurate and inconsistent due to physical limitations. Moreover, walking into rebar cages and climbing on column cages can be a potential safety hazard and can damage the integrity of the structure. The alternative method for inspecting large slabs is placing plywoods on the rebar structure as walking platforms. Although this method may be safer, the time and labor associated with moving the platforms are tedious. This can also damage the structural integrity and has a potential falling hazard as inspectors have to reach out and look down, standing on the edges of those plywoods. Figure 1 shows the current challenges associated with inspecting rebar structures. Since these visual inspections are repetitive for every jobsite, overcoming the current challenges discussed above can add value to the construction industry.

Possible visual sensing techniques that can help overcome these challenges are laser scanning and vision-based 3D reconstruction methods (Golparvar-Fard et al. 2012b). These methods can accurately create 3D point cloud models that can help determine the locations of rebars as well as spacings. Although the former is proven to be accurate and used in many incidences for quality control (Tang et al. 2011, Tang et al. 2010, and Akinci et al. 2006), it

Citation: Han, K. K., Gwak, J., Golparvar-Fard, M., Saidi, K. S., Cheok, G. S., Franaszek, M. & Lipman, R. R. (2013). Vision-based field inspection of concrete reinforcing bars. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

requires an expert for operation, is very expensive, and is not mobile. The latter, however, can provide a low-cost solution to the industry as 1) consumer-level cameras or camcorders can be used, 2) calibration is not required, and 3) experts are not required for operation.

Fig. 1: a) An inspector measuring rebar spacings (Golparvar-Fard et al. 2010); and b) the safety hazard created through the density of the rebar layers for the inspector

This paper, therefore, presents a method for assessment of rebar spacing based on vision-based 3D point cloud models. In this approach, a 3D point cloud model is created from photos taken around a rebar structure. This model is then transformed to the site coordinate system using the coordinates of a set of target points placed on the structure prior to taking photos. An area selected for inspection is segmented from the site point cloud and the locations and configuration of rebars are automatically detected. Using coordinates of those detected rebars, spacings in all three directions (*xyz* in the Euclidean site coordinate system) are determined and represented. In the following sections, the paper presents 1) an overview of the current 3D reconstruction techniques that can be used for quality control, 2) research method using the techniques discussed in the previous section, 3) results of experiment, and 4) discussion on the contributions and practical benefits.

2. AN OVERVIEW OF AS-BUILT MODELING TECHNIQUES

2.1 Laser Scanner

Today, laser scanners can provide very accurate 3D spatial data that can make them suitable for quality control related tasks. There have been many studies that illustrate the use of laser scanners in the construction industry (Tang et al. 2011, Tang et al. 2010, and Akinci et al. 2006). Despite of its proven accuracy, there are still several practical limitations that needs to be addressed. Laser scanning takes time to set up and requires experts for operation. The more dominant laser scanner used these days on jobsites are also not mobile. If used for inspecting rebar configurations, in order to minimize occlusions happening in the lower layers of rebars, the laser scanning should be performed several times at different locations from different viewpoints. The size and the way laser scanning is performed limits such repetitive activities. The costs associated with laser scanners also can limit their use, as the costs of scanners and of operating experts are still high. Other limitations of laser scanning are mixed pixel phenomenon, range errors for thin structures, range jumps at reflectance and color boundaries, and large errors due to specular reflection (Golparvar-Fard et al. 2012 & 2011, and Tang et al. 2010).

2.2 Vision-based 3D Reconstruction

The vision-based 3D reconstruction has been significantly advanced in the computer vision domain in the last decade. This advancement was partly due to improved network bandwidths and servers, computer hardware, and digital photography at low cost. All these improvements allowed the handling of large numbers of high resolution images and points extracted from those images efficiently. With the help of these hardware advancement, researchers have developed algorithms that automatically detect features and match corresponding features from an unordered set of overlapping photos, which many readers may know as panoramic stitching algorithms. One example of such algorithms is Scale Invariant Feature Transforms (SIFT) (Lowe 2004). This algorithm is later combined with Structure-from-Motion (SfM) technique, which recovers camera parameters and reconstruct a sparse 3D point cloud model from matched points (Snavely et al. 2006). These methods combined with Multi-view Stereo (MVS) algorithms such as (Furukawa and Ponce 2010) – which require camera calibration information for

3D reconstruction – can produce dense point cloud models. These algorithms in the order of which they are discussed became a pipeline for constructing 3D models using unordered images. Golparvar-Fard et al. (2012 and 2011) and Saidi et al. (2011) has applied variants of this pipeline and generated as-built 3D point cloud models for progress monitoring and quality control purposes and have proven its accuracy compared to that of laser scanning techniques.

3. RESEARCH OBJECTIVES AND METHOD

The goal of this research is to prove the accuracy of the presented method and provide the industry with an automated method that can benefit from low-cost cameras and possibly replace the current practice (i.e., manually measuring and counting rebars and using expensive laser scanner). This research explores how the construction industry, specifically quality control practices, can benefit from low-cost computer vision techniques, such as 3D reconstruction using an unordered set of digital images.

3.1 Setup and Data Collection

Before starting the inspection, a set of surveying targets are created and placed on the underlying structure of the rebars (See Figure 3). The site coordinates of these target points are extracted using conventional surveying techniques and will later be used to transform the reconstructed point cloud model from local coordinates into the site coordinate system. Once these targets are placed, the field engineer will walk around the rebar structure and will collect a large number of photos. These images and the coordinates of the targets are input to the algorithms. Here, it is assumed that the size of the rebar is known based on project specifications and the inspection task is mainly focused on assessing the spacing among the rebars.

3.2 Algorithms: 3D Reconstruction and Extraction of Rebar Locations

Given a set of uncalibrated and unordered images of an underlying rebar structure, a dense 3D point cloud model can be generated using the pipeline, of the vision-based 3D reconstruction, discussed previously. This as-built 3D point cloud model – which has an unknown scale – needs to be transformed into the Euclidean site coordinate system. This similarity transformation has seven degrees-of-freedom (DOF): *R* for rotation (3 DOF), *T* for translational offset (3 DOF), and *S* for a uniform scale (1 DOF) and can be represented as:

$$\begin{bmatrix} X_{site} \\ 1 \end{bmatrix}_{4\times1} = \begin{bmatrix} sR & T \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_{local} \\ 1 \end{bmatrix}_{4\times1} \tag{1}$$

where X_{site} and X_{local} represent the coordinates of points in site and local coordinate systems respectively. By selecting three points from both local and site coordinate systems, these seven unknowns can be calculated. Because the coordinates of these points are manually collected, there could be potential errors when transforming. Particularly there could be a user selection error due to the difficulty of choosing points with the naked eyes from the reconstructed point cloud model. Moreover choosing a minimum number of points that are relatively close to each other may not best represent the entirety of the point cloud for calculating the transformation. This is due to potential amplification when scaled up the entire model. Taking these into consideration, more target points at longer distances from each other could be selected to minimize the registration error. This can be represented in form of minimization of the sum of the squared errors as follows:

$$\sum_1^n \|e_i\|^2 = \sum_1^n \left\|\Psi_{site,i} - sR\left(\Psi_{local,i}\right) - T\right\|^2 \tag{2}$$

where $\Psi_{site,i}$ and $\Psi_{local,i}$ represent the coordinates of the targets in site and local coordinate systems respectively. To solve this equation, similar to Golparvar-Fard et al. (2009), Horn's (1987) closed-form solution to the least square problem of absolute orientation is used. Once the similarity transformation is calculated, using Eq. 1, the point cloud is transformed into the site coordinate system. To extract the locations of the rebar, one important assumption can be made based on the typical characteristics of rebar structures: rebars are mainly oriented in two orthogonal directions. Based on this assumption, similar to Saidi et al. (2011), the following steps are conducted to automatically extract the potential locations of the rebar: After the region of interest for inspection is segmented from the point cloud model, all the points are projected onto the *Z*-axis (vertical) and a density histogram of those points is generated. This histogram indicates the locations of each rebar layer in the *Z* direction (see Figure 5a).

Next, the point cloud in each separated layer is quantized into smaller volumes of subspaces (voxels) wherein for each voxel, it is assumed that the orientation of the rebar layer stays constant. For each voxel, all the points are projected onto the X and Y axes independently and density histograms representing the occupancy density of points along each axis are generated. For each histogram, the maximum peaks which represent the centerlines of rebar are identified. Here, a point x in the histogram is considered a maximum peak if it simply has the maximal value compared in the close neighborhood of the point. Once the locations of rebars for each voxel are identified, they are connected to form the entirety of the model and the center-to-center spacing between two adjacent rebars can be calculated. Figure 2 illustrates the process model for this method.

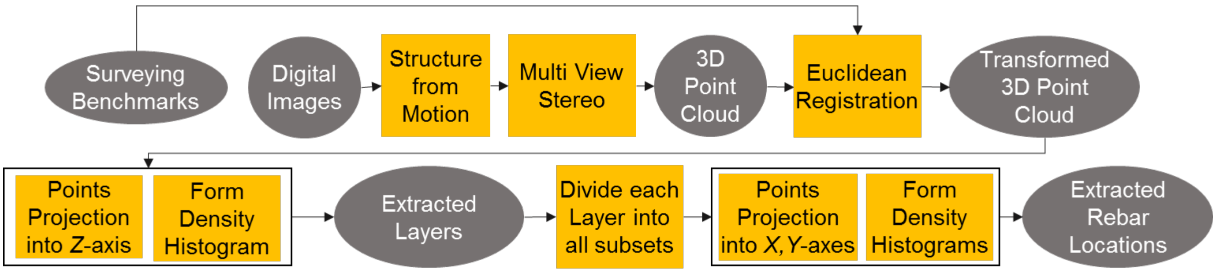


Fig. 2: The process model for the proposed method.

4. EXPERIMENT

4.1 Data Collection and Setup

The data for this research was acquired from an experiment conducted at the National Institute of Standards and Technology (NIST)'s Intelligent and Automated Construction Job Site (IACJS) testbed. The reconfigurable rebar cage was fabricated as a mockup of a typical type of rebar cage. The epoxy-coated #6 rebars are spaced at 15.2 cm and the cage consists of two layers of rebars, separated by approximately 30.5 cm. Each layer consists of thirteen 3.66 m long rebars laid on top of twenty-two 15.2 cm long rebars. To complicate the problem and embrace the real world challenges, three pipes are inserted in between the two layers, as can be seen in Figure 3. To minimize the registration error, fifteen targets were placed on the rebars as the control points. The global coordinates of these targets in the site coordinate system were retrieved using an Indoor Global Positioning System (iGPS) instrument. These coordinates were later used when transforming the point cloud to the site coordinate system. The iGPS system installed in the IACJS Testbed has a 3D position uncertainty of ± 0.250 mm and a maximum range between a receiver/transmitter pair of 40 m.

Photos were taken with a commercially available digital single lens reflex camera (DSLR). The pictures are originally taken with the spatial resolution of approximately 21.1 megapixels. Then, they were downsampled to 7.6 megapixels to match the common spatial resolution for the cameras in the recent smartphones. About 850 images were taken - later subsampled into smaller numbers of images. To minimize visual occlusion in the lower layer, a field engineer walked around the cage and took about one image per linear foot. To capture the detailed images of the center of the cage, about 50 to 70 images were taken from the top. See Figure 3 for examples of images of the cage and targets.

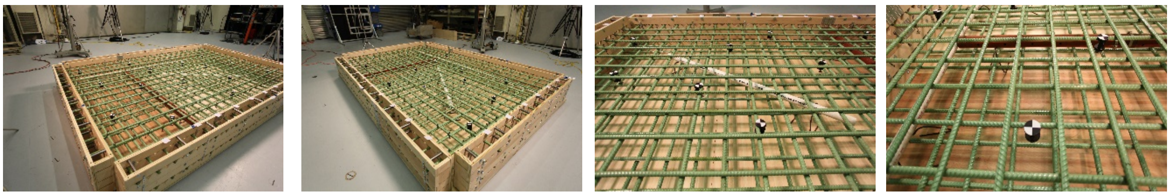


Fig. 3: The images of the rebar cage and targets used for 3D reconstruction.

4.2 Sensitivity Analysis and Discussion on the Experimental Results

4.2.1 3D Point Cloud Modeling

To test sensitivity to the number of images used for reconstruction, a subset of 100, 150, 200, and 250 images were randomly chosen. To ensure that these images were being evenly chosen throughout the structure, the structure was divided into several subareas in *x*-*y* plane. For each subarea, the visibility of points from cameras was calculated based on back-projection of each point into all cameras and checking the visibility constraints with respect to camera's field of view. This information was available as part of the outcome of the SfM algorithm. Then cameras based on their contribution to the overall 3D reconstruction were uniformly subsampled. This approach also coincided with the data collection method of a field engineer walking around the structure taking photos. For each subset of images, a 3D point cloud model was generated using the pipeline of the 3D reconstruction algorithm as discussed previously. These models were trimmed for the inspection stage. Figure 4 and Table 1 show the relationship between the density and completeness of these models with respect to the number of images used.

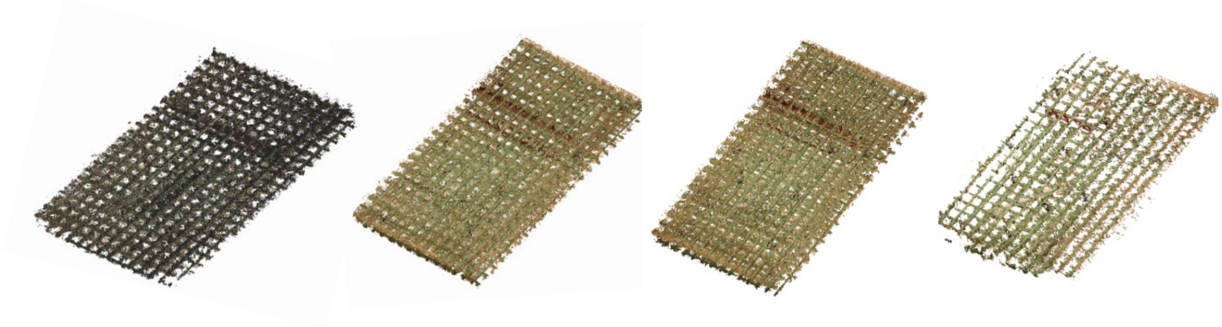


Fig. 4: 3D point cloud models from a) 250, b) 200, c) 150, and d) 100 images

Table 1: Number of points generated from each sample

# of Images	250	200	150	100
Density of the point cloud	13,320,977	10,696,247	11,554,036	1,046,101

4.2.2 Extracting Rebar Locations from Density Histogram

All the points in the reconstructed models were projected onto the *Z*-axis perpendicular to the rebar plane (*X*-*Y*). The result is illustrated in Figure 5a. As can be easily observed, the two major peaks in red boxes indicate the locations of the top and bottom rebar layers in the *Z*-axis. The top and bottom layers consist of two layers of rebars each – longitudinal and transverse rebars and the two local peaks within each box represent these two layers. Once the locations of each layer in *Z* -axis were determined, the points were projected onto the other axes and the density histograms were plotted. When projecting all the points, for instance, to *X*-axis, some information in the projected axis may be missing. For example, if one rebar was bent in a certain location, that bending will not be captured because the algorithm only shows a unique location for that section of the rebar which in this case is represented with the location with most points. To deal with this problem, as mentioned previously, the rebar cage was subdivided into voxels and the points in each voxel were projected for plotting the histograms, assuming that the rebars are rigid enough to be straight within the chosen range – 50 cm in this case (see Figure 6). Even if there is any physical damage (i.e. bent rebars), the location with most points will be relatively close to the actual location of the rebar within that small range. The shorter length can be used for finer detection of the locations but there is a risk of more points from instrument noise than points from rebars in some regions as the length decreases. For the given dataset, a length of 30 cm seemed to work. Figure 5b illustrates the density histogram of one voxel and Figure 6 illustrates how the cage was subdivided and analyzed.

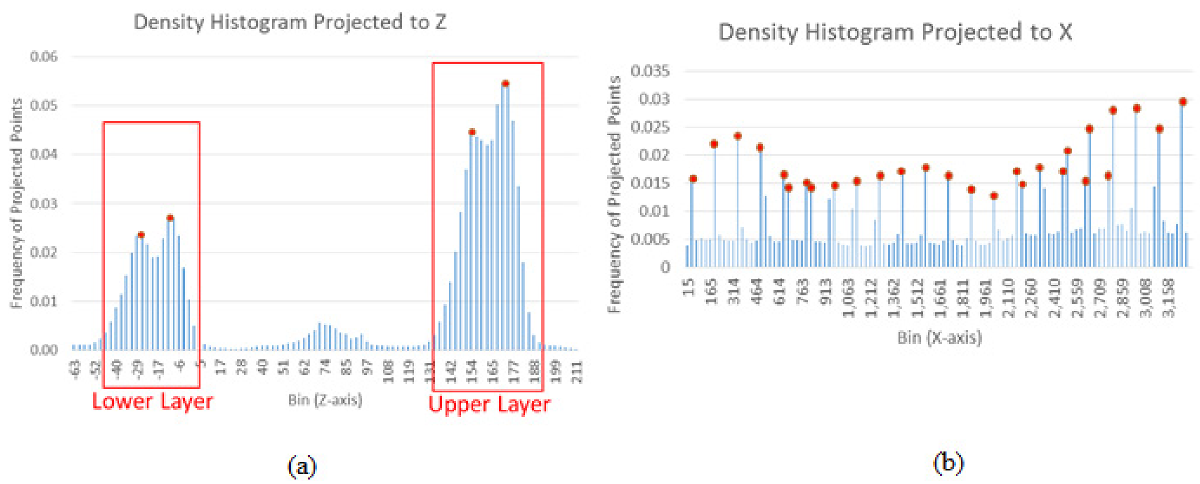


Fig. 5: Examples of Density Histogram of Points Projected to (a) *Z*-axis and (b) to *X*-axis.

The red dots in Figure 5 indicates the potential locations of the rebars and the unevenly spread dots in some areas may be an indication of the noise in the data. These red dots from the noise were ignored by comparing the possible rebar locations in one segment with the locations in the other segments. Because a rebar will be almost always straight within a short length (i.e. 50 cm) unless its configuration is significantly irregular, any outliers can be ignored. Lastly, the density histograms of the points projected onto the *Z*-axis for every 50 cm × 50 cm are plotted to capture more accurate locations of *Z*-coordinates throughout the structure. Figure 8 illustrates the intersections of the rebars and shows how the rebars are deflected towards the center of the rebar cage. Note that *Z*-axis is exaggerated for the illustration purpose.

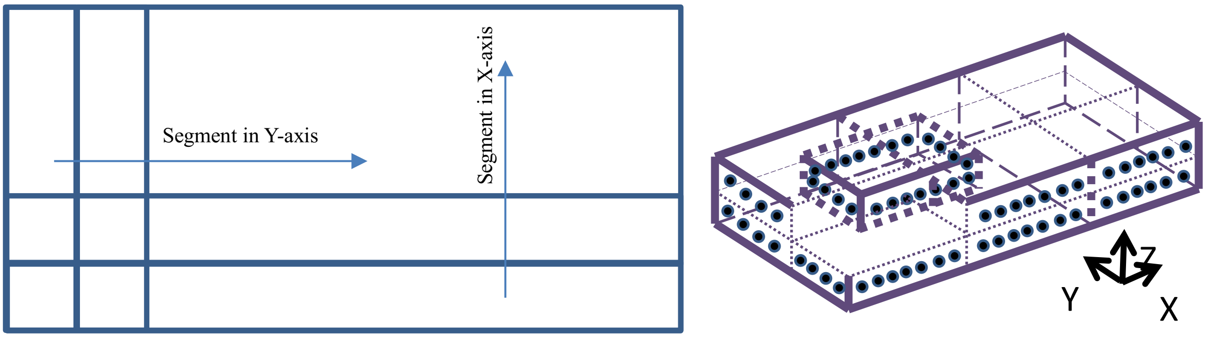


Fig. 6: Illustration of how the rebar cage is segmented: top view on left and 3D view on right.

4.2.3 Validation

A 3D point cloud model generated from a laser scanner was used for 1) validating the accuracy of the 3D

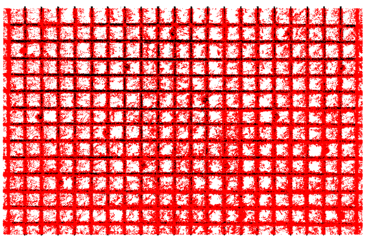
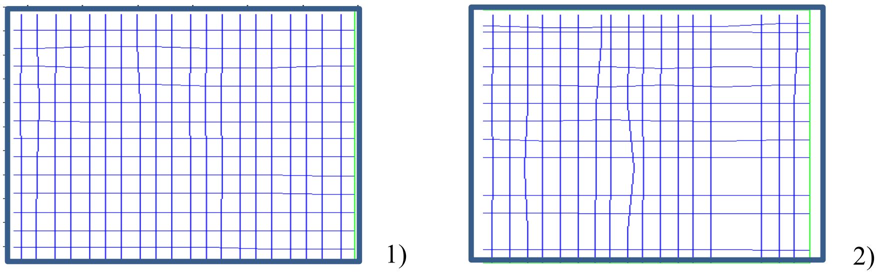


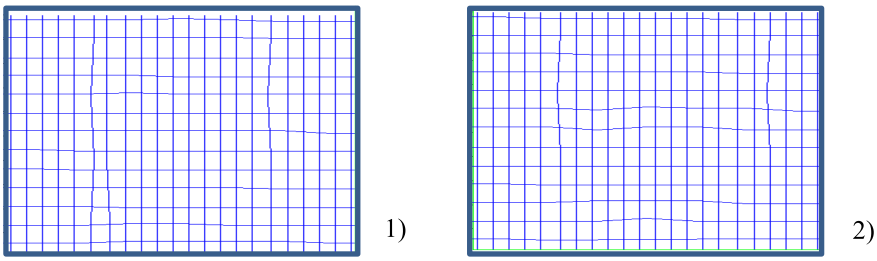
Fig. 7: Superimposed point cloud models (red: vision-based reconstruction and black: laser scanning)

reconstruction and 2) running the same algorithms with the laser scanned model to test which of those two 3D models provides a better result. The accuracy of 3D reconstruction was tested by Golparvar-Fard (2012b) and the registration error was less than 1 mm registration error when 15 targets were used by comparing it to a BIM model. For this reason, this research only tested the accuracy of the point cloud model by superimposing it into the point cloud model of the laser scanner and visually examining the results of 3D reconstruction. As seen in Figure 7, the accuracy of the vision-based reconstruction looks promising.

The extracted locations of the rebars are plotted in 2D (top view) and 3D and displayed in Figure 8 and 9, respectively. Figure 8a illustrates the results from the laser scanner and Figure 8b illustrates the results from the vision-based 3D reconstruction using 200 images. Because the laser scanning was performed once, it had limited visibility, which is why some of the rebars in the lower layer were not detected due to occlusions of the inserted pipes. On the other hand for the vision-based approach, every rebar was successfully detected as it used images taken from different perspectives which minimized the chance of occlusion. As the number of images decreased, the occlusions became apparent (see Figure 10). Notice the upper layer that is always free from occlusion and almost always detected all the rebars in all cases, whereas the lower layer with occlusions was very sensitive to the number of input images. More images meant less occlusion as more viewpoints became available.



a) Output of rebar detection algorithm from laser scanning point clouds: 1) upper & 2) lower layer



b) Output of rebar detection algorithm from vision-based point clouds (200 images): 1) upper & 2) lower layer

Fig. 8: Detected rebar layouts for laser scanner (top) and vision-based (bottom).

Since the rebars are only supported around the edges of the cage by the formwork, there is deflection towards the center of the cage and this was also successfully captured as illustrated in Figure 9. Partial rebar spacing is given in Table 2 due to space constraint. The results look promising when compared to the actual spacing of 15.2 cm, considering that there could be small error in placement of the rebars into the cage. All the results for the vision-based reconstruction using 250 and 200 images were within the tolerance of 7.6 cm to 10.2 cm (3 in to4 in) defined by ACI 117 (CRSI 2011). Notice that the z-coordinate is determined and assigned for each $50cm \times 50cm$ subarea. This is acceptable since deflections are so small that it is even hard to see the actual deflections with eyes. The largest deflection (difference between the highest and the lowest z-coordinate) was $1.5cm$. For more accurate distribution of z-coordinates, the size of the subarea can be decreased but not smaller than $30cm \times 30cm$ by the authors' experience.

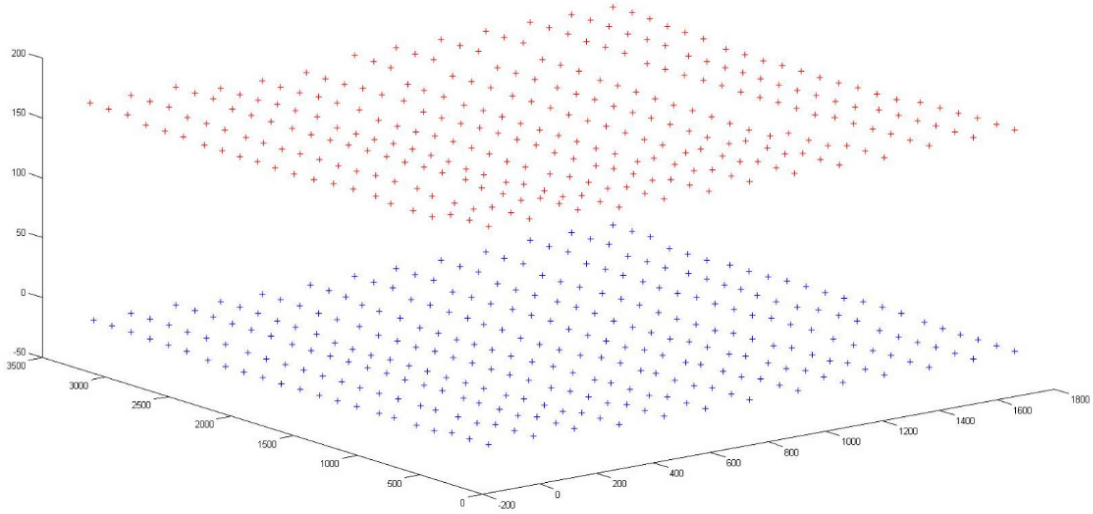
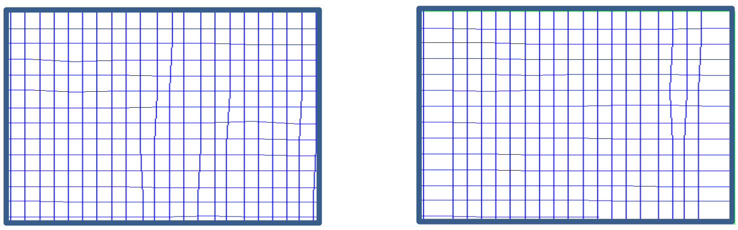
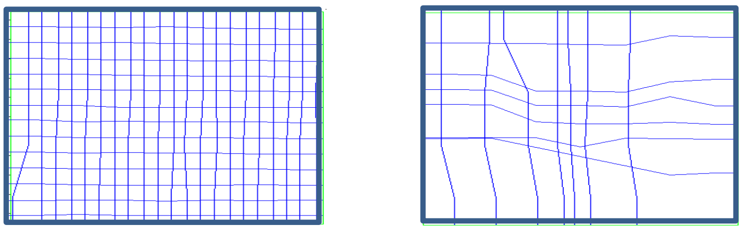


Fig. 9: Plotted rebar intersections.



a) Output using 150 images: Upper layer on left & lower layer on right.



b) Output using 100 images: Upper layer on left & lower layer on right.

Fig. 10: Output from vision-based reconstruction

Table 2: Spacing output from the vision-based reconstruction using 200 images. First 13 results of the second line from the bottom in *x*-direction.

Lower (cm)	15.6	14.4	15.6	15.6	14.4	15.6	16.8	15.6	14.4	15.6	15.6	14.4	15.6	14.4
Upper (cm)	14.4	16.8	14.4	15.6	15.6	14.4	15.6	15.6	15.6	15.6	15.6	14.4	14.4	16.8

This research can potentially be used in conjunction with the 4-dimensional augmented reality (D^4AR) modeling which Golparvar-Fard (2012) has developed for progress monitoring. In that system, an as-built point cloud model is generated from images and superimposed with IFC-based Building Information Models (see Figure 11). A rebar structure in that point cloud model for progress monitoring can be segmented and inspected at the same time. With more photos for denser and accurate 3D reconstruction, this system can also perform quality control related tasks, such as checking rebar spacing.

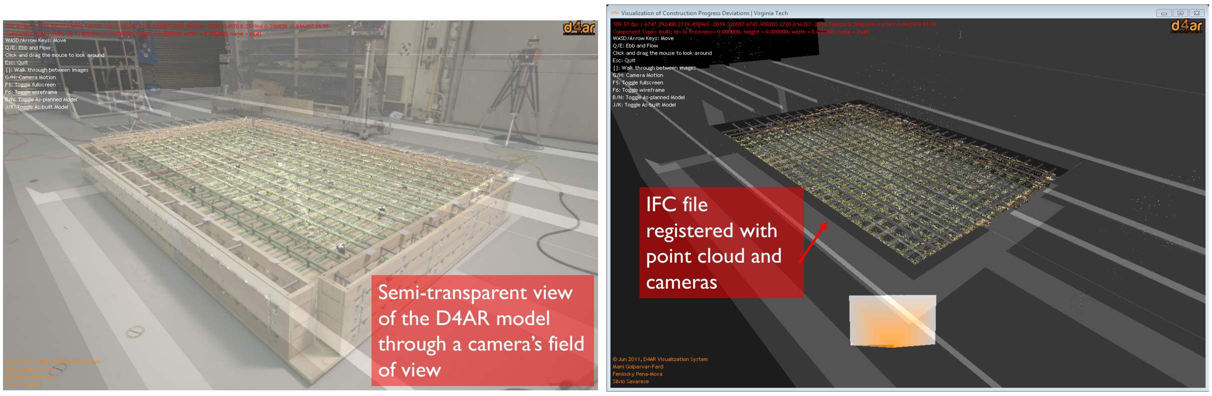


Fig. 11: The cloud model superimposed with IFC-based BIM model via the D^4AR

5. CONCLUSION AND FUTURE RESEARCH

This paper presented the vision-based field inspection of rebars for concrete slab structures. The results of this research show how digital images can provide the detailed information that can be used for quality control. The results also proves the accuracy of such information is even comparable to that of the laser scanning method. It was shown that this vision-based approach using the images yielded better results than using the laser scanner in the presence of occlusion. It was also shown that the number of images had a great impact on the quality of the 3D reconstruction and therefore on the quality of the rebar detection. The results show that the vision-based approach using digital images can provide low-cost field inspection and has the potential to replace the current labor-intensive and unsafe visual examination, measuring and counting of each and every rebar.

Inspecting more complex structures in an uncontrolled environment will be studied in future work. This study can also expand to inspecting lap slices, stirrups, and rebar cages with more irregular configuration. The geometry fitting into possible rebar locations shown by peaks in density histograms will be studied. This can improve the process of choosing inliers against possible outliers. This approach can detect lap splices as it will search for cylinders in a given range around each location of the peaks and can also differentiate between sizes of rebars by fitting different size cylinders. The main goal is to automate and expedite the whole inspection process, which eventually can eliminate idle time prior to pouring concrete. These are all being explored as part of an ongoing research project and results are forthcoming.

6. AKNOWLEDGEMENT

The authors would like to thank the support and help of C. Brown, J. Swerdlow, I. Katz of NIST and B. Ghadimi, and M. Akula with data collection and experimental setup.

7. REFERENCES

Akinci B., Boukamp F., Gordon C., Huber D., Lyons C., and Park K. (2006). A Formalism for Utilization of Sensor Systems and Integrated Project Models for Active Construction Quality Control, *Automation in Construction*, Vol. 15, No. 2, February, 2006, pp. 124--138.

Casey M. J. and Urgessa G. S. (2013). Rebar Cage Construction and Safety: Best Practices, *Construction Institute*, American Society of Civil Engineers.

Concrete Reinforcing Steel Institute (CRSI) (2011). Field Inspection of Reinforcing Bars, *CRSI Technical Note CTN-M-1-11*, Concrete Reinforcing Steel Institute.

Furukawa Y. and Ponce J. (2010). Accurate, Dense, and Robust Multi-view Stereopsis. *IEEE Trans. Pattern Analysis and Machine Intel.32,1362–1376.*

Golparvar-Fard M., Peña-Mora F., and Savarese S. (2012a). Automated Progress Monitoring Using Unordered Daily Construction Photographs and IFC-Based Building Information Models, *J. Comput. Civ. Eng.*, 10.1061/(ASCE)CP.1943-5487.0000205 (Feb. 11, 2012).

Golparvar-Fard M., Ghadimi B., Saidi K., Cheok G., Franaszek M., and Lipman R. (2012b). Vision-based 3D Mapping of Rebar Location for Automated Assessment of Safe Drilling Areas Prior to Placing Embedments in Concrete Bridge Decks, Construction Research Congress 2012: pp. 960-970.

Golparvar-Fard M., Bohn J., Teizer J., Savarese S., and Peña-Mora F., (2011), Evaluation of Vision-based Modeling and Laser Scanning Accuracy for Emerging Automated Performance Monitoring Techniques, *J. of AutoCon,* 20(8), 1143-115.

Golparvar-Fard, M.U, Fukuchi, Y., Peña-Mora, F., and Savarese, S. (2010). "D^{4}AR – 4D Augmented Reality – Models for As-built Visualization and Automated Progress Monitoring of Civil Infrastructure Projects." *Proc., 10th Int. Conference on Construction Applications of Virtual Reality 2010*, Sendai, Japan, Nov 4-5.

Golparvar-Fard M., Peña-Mora F., & Savarese S. (2009). D4AR - A 4-Dimensional Augmented Reality Model for Automating Construction Progress Data Collection, Processing and Communication. *J. of ITCON, 14*, 129-153.

Horn, B. (1987). Closed-form Solution of Absolute Orientation using Unit Quaternions. *J. of the Optical Society, A(4)*, 629-642.

Lowe D. (2004). Distinctive Image Features from Scale-invariant Keypoints. *Int. J. of Computer Vision,* 60(2), 91-110.

Saidi K., Cheok G., Franaszek M., Brown C., Swerdlow J., Lipman R., Katz I., Golparvar-Fard M., Goodrum P., Akula M., Dadi G., and Ghadimi B. (2012), "Development and Use of the NIST Intelligent and Automated Construction Job Site Testbed". *NIST TN 1726*, National Institute of Standards and Technology, Gaithersburg, MD, Dec, 2011.

Snavely N., Seitz S. M., and Szeliski R. (2006). Photo Tourism: Exploring Photo Collections in 3D. *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2006), 25(3), pp. 835-846, 2006.*

Tang P., Huber D., and Akinci B. (2011). Characterization of Laser Scanners and Algorithms for Detecting Flatness Defects on Concrete Surfaces, *J. Comput. Civ. Eng.*, 25(1), 31–42.

Tang P., Huber D., Akinci B., Lipman R., and Lytle A. (2010). Automatic Reconstruction of As-built Building Information Models from Laser-scanned Point Clouds: a Review of Related Techniques, *J. of AutoCon*, 19, 829-843.

ADOPTION OF BUILDING INFORMATION MODELLING (BIM): AN EVALUATION THROUGH A CASE STUDY OF A REGIONAL CONTRACTOR

Kelly Paine & Ramesh Marasini
Maritime and Technology Faculty, Southampton Solent University, East Park Terrace, Southampton SO14 0YN

ABSTRACT: *The Building Information Modelling (BIM) has been adopted by construction companies in the UK owing to the stipulated potential benefits and a push for its widespread uses on a national level though the new Government Construction Strategy. Large companies in the UK and the BIM software industry have suggested that the benefits of the technology are higher than the associated costs. This paper investigates challenges and issues faced by a regional contractor specialising in building projects under most Forms of Contract, including Design and Build and Traditional Contracting. Through a case study of a regional contractor, the process of implementation using BIM framework such as BIM plan and strategies is evaluated. The challenges as well as considerations that need to be taken into account in order to achieve, if at all possible, integrated building information model through the integration of architectural, structural and MEP models are evaluated and discussed in the paper.*

KEYWORDS: *Building Information Modelling, Regional, Contractor, Adoption, Challenges*

1. INTRODUCTION

Building Information modelling (BIM) is a term to describe a set of technologies and a group of processes within the architecture, engineering and construction (AEC) industries and the outcome is 'an accurate virtual model of a building digitally constructed' (Eastman et al 2008). The virtual model, if fully integrated, contains information on multiple facets (planning, cost, sustainability, H&S etc.) of construction projects throughout their whole life cycle such as design, procurement, construction, operations (facilities management) and demolition of the constructed facility. The development and subsequent use of the BIM models therefore require the entire project team to work collaboratively. Case studies, published to date, have demonstrated that the use of BIM will result in better quality of built facilities at a lower cost and reduced programme duration.

In May 2011 the Government issued a Construction Strategy and a mandate for a 'fully collaborative 3D BIM as a minimum by 2016'. Since publication of the strategy, the term has been widely used in the construction vocabulary (Cabinet office, 2011). The uptake in the industry currently varies between one business to another and to the extent in which BIM is used. Some companies will be gradually working towards an integrated practice and others using the minimum they can to facilitate requirements where necessary.

Many companies also pay lip service ('Bimwash') to BIM, making unwarranted claims of use and being BIM literate (BIMe 2012). Such claims could be due to BIM being misunderstood, and contractors trying to overcome the complex issues involved with its implementation or purely for the hope of satisfying clients. This is mainly because of confusion about what it is, how it should be utilised and implemented, how to resolve challenges that are faced with its implementation, where to start and how to integrate BIM within the business.

There are a number of industry wide known issues with the adoption of BIM, that are commonly discussed. The challenges are costs to acquire the technology, skills required to utilise the technology and cultural changes required within the industry. Other challenges are: ownership & transfer of responsibility of the model during stages of the project, liability and insurance and model management including change control (McGraw-Hill Construction 2009).

Clients and designers in the supply chain are favouring the technology. Large companies who have resources and the ability to go through the change process are also pushing the use of BIM in construction projects. As expressed in the UK Contractors Group report, Construction in the UK (2012), the UK construction industry is a significant contributor to the domestic economy in the UK. The report states that "when the entire supply chain is

Citation: Paine, K. & Marasini, R. (2013). Adoption of building information modelling (BIM): an evaluation through a case study of a regional contractor. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

considered the industry contributes up to 14% of GDP and historically is a key driver in GDP." As approx. 99% of the companies are small and medium sized companies (SMEs), therefore, the importance and acceptance of any new technology by SMEs including regional contractors would be a key in its development and success throughout the industry. The challenges in adopting BIM down the construction supply chain such as regional contractors and SMEs are very significant. There are several case studies published from the clients and large construction companies, this study provides medium sized contractors perspective.

Some of the questions that need to be asked are: what is required by a contractor to meet the Governments mandate? Will BIM ensure long term growth and client satisfaction for the business? What for and how should be BIM be used? How should BIM adoption be approached? What documents should be used for its implementation?

This paper aims to answer these questions through a review of a case study of the processes used in BIM adoption by a regional building contractor and provides suggestions for BIM's use within the medium to small businesses. A number of aspects of BIM implementation were observed which include the effort gone in to the business as they commence the learning curve of producing a BIM Model, and subsequently using the BIM functions on a pilot project; the changes the team have had to make and how the team performed, along with how the key BIM Software has performed. The findings through a semi-structured interview with a director involved in the implementation of BIM are also presented in this paper.

2. WHY AND HOW TO IMPLEMENT BIM?

The concept of BIM is for it to benefit designers, including supply chain, project managers, planners, estimators and quantity surveyors, enabling the whole supply chain to collaboratively work together. Identified by the BIM Taskgroup (Department for Business Innovation & Skills, 2012) BIM is not software. It is more than 3D modelling but a business process, and therefore one cannot go out and 'buy BIM'. BIM is technology and a new way of working, tools which improve delivery and implementation of a collaborative culture. Depending upon the competencies and business process, 4 levels of BIM have been defined (BIM Maturity wedge, Richards and Bew 2008 cited in Department of Business, Innovation and Skills 2011).

Level 0 is where BIM is used as a CAD tool to produce 2D drawings, as traditionally. The coordination is usually completed by hardcopy of paper drawings. **Level 1** is a basic Level of BIM and may use some 3D modelling. However information is coordinated using information management protocols. Some of the protocols are shown in the model such as Avanti, CPIC, and BS1192:2007. **Level 2** is the production of a 3D model of the building, where each element is modelled using parametric data. The model at this level will produce all 2D and 3D drawings, where if a change is made in one place, the model will update automatically everywhere. **Level 3** is an ultimate stage which is descried as 'fully interoperable' BIM. It is a fully integrated way of working. One model is created, coordinated (integrated) and shared. All work by each discipline is completed on the same 'live model' requiring all of the project team to have the knowledge, skill and willingness to work in this way. Through virtual design, as the model acts as a true representation of the building and hence supports theoretical building design analysis, to check things such as: sustainable design solutions, lighting analysis and value engineering as well as more.

In a study completed by McGraw-Hill Construction, 'The business value of BIM' (2009), there seems to be a consensus of the BIM Benefits contributing the most value to a project, including reduced conflicts, improved collective understanding of design intent, project quality, reduced design, construction changes and RFI'S, and the better cost control. In addition some key benefits highlighted in the literature include: increased communication, sharing information utilising a centralised filing for information exchange; collaborative design and construction in all project stages; pricing accuracy and a reduction in time producing cost estimates; system analysis, such as sustainability, air flow and energy modelling.

The National federation of builders (NFB) produced a report in 2012 called 'BIM-readiness survey 2012' looking at BIM-readiness in the contracting sector with responses from a broad cross-section of the industry, from micro enterprises to the very largest contractors. The survey highlights that industry will need to make this leap at a time when resources are most stretched, competition is high and lower demand for the work and specifically for SMEs, it seems far from reality. The survey indicates awareness of BIM and recognition of its importance, but a low level of understanding of BIM. It suggests that there is currently a general unwillingness to invest and develop in BIM capability. For successful implementation of BIM, it really needs to be understood what is meant by BIM and further more a cultural paradigm shift in the construction industry is needed as identified by Waterhouse (2012). This is the shift talked about in the Egan report (1998) of collaborative working, and the way to get there is education and training. This will of course be a major learning curve for many organisations such as contractors.

Many reports discuss the investment required by contractors to implement BIM. Gaining experience in BIM needs investment in many products and processes. In the SmartMarket report 2009 by Mc Graw Hill construction, they describe key areas of BIM investment as, software, collaborative working, marketing BIM capability, training, hardware, interoperability, developing 3D libraries. Training of staff to acquire BIM modelling will be one of the first start-up costs to be considered by contractors. It will be correct to assume that contractors will rely on external consultants to carry out training initially. Epstein (2102) comments that eventually contractors will develop their own in house training programmes, where staff training can then be done by in house technical experts for long term viability.

There are still known challenges with the transferring of BIM files between different software as interoperability has become a major problem. Software packages tend to work on a suite approach with specific versions for the Architect, Structural Engineer and M&E engineer to work within, the transfer of information between different software suites can cause issues. The solutions required will more than likely need to be found by the user, as they will be dependent on specific situations, for example what software is in use and what functionality is required as the output. As BIM tools are rapidly developing, the use of open file format such as Industry Foundation Classes (IFC) should provide standard BIM model where information can be shared across by the different participants in a project. This however highlights the importance a regional building contractor's decision will be when choosing which software to purchase.

The National BIM report (Waterhouse 2012) suggests research and anecdotal evidence indicate that some sectors are prepared to invest earlier than others in BIM, with medium and large scale constructors seeing the benefits and investing in the use of BIM. One of the problems with up take by regional contactors is the level of initial investment required as discussed previously. Waterhouse 2012 state this leads to contractors being unsure on up take and delays contractors while they wait for further evidence that BIM represents a good investment. They quote that "the idea BIM is only for big business is challenged by the growing number of small and medium enterprises that can demonstrate a return on investment."

The questions highlighted within the National BIM report (2012) that often are asked by contractors on BIM implementation, are "How do we get started?" and "How do we ensure that when we invest, we get a return and do not buy into a dead-end technology?" The case study discussed in this paper attempts to provide some answers to these questions.

Multiple industry standards have been published to establish a common practise across the industry for BIM protocols including CAD standards. These guidelines build up the AEC UK BIM Protocol including BS1192:2007 and PAS1192-2:2012 (AEC UK 2012). The Construction Users Round Table (CURT 2010) provides guidelines for the BIM implementation using life cycle approach in three main stages: Project Pre-Planning; Design & Construction; Operations & Maintenance. This study mainly looks at project pre-planning and design stage and the impact of adopting BIM from functional perspective. This study used 'federated model' concept where component models were combined for coordination only with component model creators retains responsibility and ownership.

3. FACTORS TO BE CONSIDERED FOR IMPLEMENTATION

The BIM implementation literature review highlighted a number of factors that particular affect a business' BIM implementation. The variables have been summarised in Table 1. Before a business starts it's BIM implementation the Government Construction strategy advises the maturity wedge is used to understand what level a business is currently working at and agree the level the business needs to be at or would like to achieve. The AEC UK BIM Protocol described, is the basis document for a company to use in producing its own BIM strategy. The AEC make recommendations for a high level company strategy based on the AEC protocol to be produced. The document is to assist the development of a consistent BIM across all disciplines to ensure that the coordination and information exchange process can be managed and a successful fully coordinated BIM is achieved.

Table 1: Factors to be considered for BIM adoption

Decision Variables	Considerations
BIM Readiness	Review the company's position and capabilities, and ask, is the business ready and set up to be successful with BIM.
Client Demand	What clients, will benefit from BIM, can the company market its new capabilities.
Government Strategy	Government construction mandate and sustainability agenda.
Staff training	Capital required to train staff, will be one of the first start-up costs. The willingness of staff to embrace a different way of working and their tolerance for change.
Funding and Cash-Flow	Business investment is needed in the form of purchasing numerous software, marketing BIM capability, training, hardware. All needing time and resource to carry out.
Legal implications	Business insurances may need to be revised, Contracts, ownership of models legalities.
Technology Capabilities	Understanding software and its functionalities and Interoperability issues with software.
Supply chain BIM Competency	How will the business integrate its supply chain? How will it evaluate which consultants to use on its BIM projects?

4. CASE STUDY

4.1 Rationale for Using a Case Study

Case study method is used to find answers to research questions mainly "how" and "why" and is preferred in examining contemporary events (Yin, 2009). The strength of case study as highlighted by Yin is the ability to deal with variety of evidence such as documents, artefacts, interviews and observations. In the study of BIM implementation, a case study of a pilot project where a regional contractor was undertaking BIM implementation was selected. The contractor is a regional construction company operating across southern England. The company undertake a wide range of projects and under most Forms of Contract, the two main areas are Design and Build and Traditional Contracting. The project included a new school, which is a design and build project with a price of 30 M pounds. The team consists of six people, from different disciplines: structural design manager, architectural design manager, estimator, planner, MEP manager and technical department manager.

A detailed single case study method with exploratory analysis was used in order to analyse the issues that should be considered by regional contractors in BIM implementation and hence the objective was to expand and generalise theories, not statistical generalisation (Yin, 2009), and mainly to understand the BIM implementation better from regional contractor's perspective. The data collected for the case study were direct observations of the processes followed by the BIM team; the technical difficulties encountered and solutions utilised were recorded and evaluated to identify the challenges faced during the BIM implementation. The information from weekly design and BIM Co-ordination meetings, progress of work and informal discussions with the BIM team were collated. An interview was conducted with the business technical director and key points from the interview are discussed in the following sections. The findings from the case study provide lessons learned during the process and hence help the decision making process that should be used by regional contractors. The legal aspect of the BIM is outside the scope of the paper.

Normally it is expected that BIM model is produced by the designers and consultants and passed down to the contractor. The contractor can use the model to interrogate and modify information within the model where needed and use the model in assistance with the bid for planning, costing and logistics. In this case the project being design-build and only 2D drawings existed for the project, the contractor produced the model themselves from 2D information with an in-house team and employment of consultants on MEP design. The decision to implement BIM was taken as there was a 6 month period before the project can commence. Therefore it was deemed to be an ideal opportunity to use the 2D information from the school to produce a model and be able to carry out BIM functions and comparisons.

A number of key business goals were identified by senior management to be included in a BIM Execution Plan which included complete principle training for the team; develop a pilot project; develop a revised short, medium & long business plan; build in-house capability for future projects and provide fully coordinated BIM including MEP showing a cost benefit.

4.2 Technical aspects of BIM on the pilot project

With senior management commitment to adopt BIM and test through a pilot project, the team consisting of six people from different disciplines was tasked with the experimentation of BIM. The team consisted of a structural design manager, architectural design manager, Estimator, Planner, MEP manager, Technical department manager. The goal of the pilot project was to create a model to be used to determine what is involved with BIM and each of its functionalities, and what the software can produce. By carrying out the project, it has been realised that the software chosen needs to best fit the company's needs.

It is important before each project commences a clear objective of what BIM outputs are required and what they will be used for is understood by the whole team. These objectives will be included in a Project BIM execution plan. A BIM action plan was prepared and the team was trained with a vision to build in-house capability for future projects. A fully co-ordinated BIM for the pilot project was created, comprising of a separate, Architectural BIM, Structural BIM and MEP BIM. The fully combined BIM was used to explore clash detection procedures, 4D (3D+time) aspects of BIM, and energy modelling. The main functions of BIM have been analysed below in Table 1, different software is required to enable these functions to be carried out. The facilities management of the assets and demolition stages are outside the scope of this paper.

The BIM functionalities modelled and evaluated in the case study include the 3D co-ordinated model creation, clash detection, visualisation, sequencing, quantity take off and energy and environmental modelling, which are discussed briefly in the following sections.

4.2.1 Model Creation: 3D Parametric Model

The first step used was to create a 3D model with parametric and information-rich objects which can produce 2D drawings and create output files that conform to the IFC (Industry Foundation Classes).The structural and architectural models were produced separately using Revit Structure and Revit Architect by the Contractor's in-house team. The models took approximately 2 months to complete. It seemed to be a very steep learning curve for them to get it all right and the 2 months to produce the model included large elements of self-teaching (Figure 1). 'Model Development Method' (AEC UK 2010) was deployed to understand the level of detail required at stages of the model. When constructing the model, it was found from the pilot project that an unclear scope of what is required in the model and what the model will be used for, would slow down creation of the model leading to increased cost and delay to programme. During the case study it was found objects can be too simplified for what is required or over modelled, with manufacturers modelling every screw and bolt. A MEP model for the project was prepared by consultants using Autodesk Fabrication MEP and Navisworks was used for the rendering and animations.

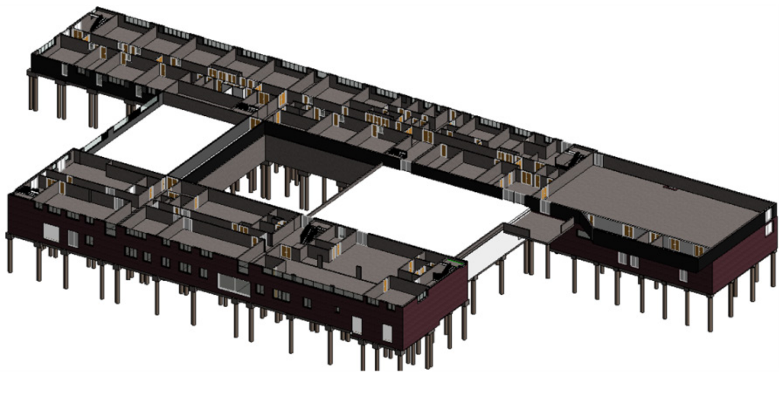


Fig. 1: 3D model of School Building with Architectural and Structural details

4.2.2 Model Co-ordination and Model Clash Detection

Navisworks was used to co-ordinate single discipline models into one file prior to clash detection and full design coordination. Once structural, architectural and MEP work-in-progress models were created as an entity, all 3 models were brought together and used for clash detection. The aim of the clash detection exercises was to model pinch point areas and highlight risk hotspots. Design coordination issues were clearly visible, the models were then released back to the originator to workout appropriate solutions (Figure 2).

This brought about problems, with different versions of the model still being worked on, while co-ordination and clash detection exercise were taking place. When the model was returned with the comments, an updated version already existed. A procedure was created to overcome the updating of the models. The procedure lets each designer know when they could work on the model again.

Over 1000, clashes and errors were identified during the pilot project, approximately 20 of which resulted in significant cost savings. The detailed analysis of savings was not carried out in this study. Without BIM the majority of these clashes, with duct work being below ceiling level, and interface issues with risers would not have been detected until the actual construction had taken place on site, this could have potentially caused additional cost and time to the project.

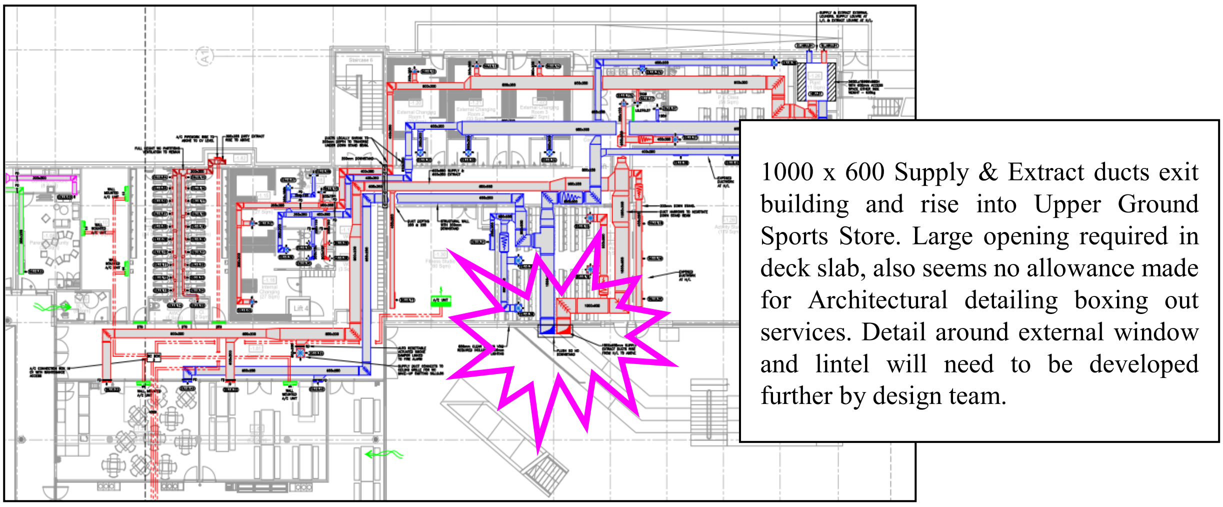


Fig. 2: Clash detection and solution

4.2.3 Sequencing

The programme for the project was developed in Primavera and was imported in to Navisworks along with the 3D co-ordinated model. It was found additional activities needed to be added in to the programme to provide the details required, to have a timeline to show each object in the model, this gave a more detail construction visualisation. Owing to lack of functionality to export programme activities created within Navisworks, alternative software, Synchro was used so that Primavera and MS Project files could be created directly from the software.

The model can be used to communicate to subcontractors is a better visualisation way for them to understand the construction methods on projects. This brings about more of the collaborative working and utilises other function that BIM can complete. For construction process visualisation, components library for cranes, site welfare accommodations, propping, safety platforms etc were created, which can be used again by the business saving time on modelling.

4.2.4 Visualisation

Navisworks Freedom worked well for viewing the model although some hardware used by staff was not sufficient to use the software well- this may be due to the specification or age of the equipment. A review of staff needing an upgrade of hardware will need to take place to utilise the software to its full potential. Some staff were also not IT literate enough to use the software, therefore some training needs to be given on using the tools contained within the software, to view and obtain data.

4.2.5 Quantity Take Off

Revit 3D Model was used to complete the quantity take off and compared with the traditional take off method using Excel. To develop the model, other software didn't present any specific advantages. Different measurement software linked to Revit exist: Autodesk Quantity Takeoff, Causeway BIM Measure and VICO Take-Off

Manager. The Causeway and Vico software were investigated. The comparison revealed problems with accurate comparisons with some issues in the model and the way it is built. To receive accurate quantities from BIM a set of modelling procedures needs to be adhered to. However when these procedures are correct, it is simple to extract the quantities and information required from BIM, in comparison with estimators having to carry out their own quantity take offs, or employing someone to produce a bill of quantities. Discrepancies were identified; investigation showed that most of the discrepancies were due to design changes. Some other differences were due to the differences in classifications in the traditional take off and the classifications received out of Revit and modelling inaccuracies. The way certain elements were built, overlaps in what is modelled for example would cause Revit to include the quantity of that object twice.

4.2.6 Energy and Environmental Modelling

Software called Thermal Analysis Simulation (TAS) was used to review the mechanical and electrical design efficiency of the building. The model took approximately one week for the MEP specialist to draw in the software using the architectural model. Fabric U-values were added and material properties assigned to the model. The passive design measures used in the building design were tested using different fabric U-values, air-tightness and facade G-values to meet maximum solar gains, overheating and day lighting targets.

A simulation on the building, such as the amount of heat released in the building took about 10 minutes. To achieve the required figures for the project, it took 11 simulations. One of the main benefits for the business is that the MEP Manager can interrogate the model easily. For a regional building contractor, in general the M&E consultants would provide most of the information generated from the software. However being able to use the software to validate a design, to use to review high level build-ability, and challenge a consultants design was found beneficial. Overall, the co-ordinated BIM model outputs put the contractor more in control.

4.3 Findings from the technical evaluation

The findings of the technical evaluation of BIM model development process has been presented in Table 3.

Table 3: Technical Evaluation of BIM - Pilot project

BIM Steps *(Software used)*	**Challenges**	**Problems**	**Solutions**
Model Creation *(Revit Structure & Revit Architect)*	Identifying level of details required in the model.	-Unclear scope, unmanageable file sizes, inefficient time spent modelling.	Agree the max level of detail to be included in the BIM agreed. Too little, model may not be fit for purpose; too much detail leads to large and inefficient model.
	Establishing the parameters required	Too much time spent adding data that may not be used in the model.	Provide a clear brief with milestone tasks for review. Do not include the details hoping it may be useful in future.
Co-ordination and Clash Detection *(Navisworks)*	-Various iterations of the designers' work-in-progress.	Models being updated before co-ordinated and clash detection had been finalised.	Establish model update controls such as Green Light Management system. When green light is on, model can be worked on by all disciplines.
	Functional models may be designed in specific software.	Interoperability amongst the models created in different software.	Establishing a common platform (if available) for all designers is key to successful integration.
Sequencing *(Naviswork, Synchro, MSProjec, Primavera)*	Linking model to programme.	Models produced individually until they are brought together and overlaid to produce a version, or 'issue' of a BIM model.	Use a software which has import and export functionalities, also naming different sets in the model same as operations description in the programme for automatic linking with 3D model.
Quantity Take off *(Revit)*	Achieving a 'like for like' on quantities.	In accuracy in model, in the way drawn, to hinder accurate quantity take off.	Estimators and BIM modellers - produce a combined procedure, for modelling specific elements that can then be used for quantity take off measures.
Visualisation *(Navisworks)*	Hardware requirements of staff	Hardware upgrades required as models slow or incorrect display	Business to develop computer hardware strategy for each department and establish purchasing of correct hardware.

Energy and Environmental modelling *(TAS)*	Should the business as a regional contractor need to carry out these functions?	A role for this developed and a new person brought in to the business or an existing employee trained for the role	At high level, the function can be used by the BIM team to carry out simulations to interrogate a consultants design and review other design options.

Through the discussions with the BIM team within the pilot project, it was evident that there is no evidence to suggest that the process disrupted company's established workflows. The learning of the software was a steep curve. In order to have integrated BIM model, lack of single platform and interoperability was still a key hurdle in the process.

4.4 Semi-structured Interview: management perspectives

A semi structured interview was conducted with a director involved in the decision making to adopt BIM in the company who was closely working with the BIM piloting team. 13 open ended questions were used in the interview, which are presented in the Appendix 1. The objective of the interview was to obtain relevant information about the experiences through the pilot project, questions on if the pilot project met expectations, and queries if the business now has the learning required to facilitate further BIM use in the business. The summary of the interview has been presented in Table 4 using the same variables identified in the literature review. The interviewee highlighted the benefits of BIM to the business as "BIM will definitely bring greater certainty, less errors and omissions on projects, clearer on site tracking of information, and enhanced coordination between design team members. The clarity for clients means we can help deliver their needs better, continual production of handover information, handover information in useable formats, and with the opportunity to standardise across the business."

Table 4: Interview Analysis

Implementation Factors	Analysis Variable	Interviewee Responses
BIM Readiness	Motivation	Directors of the business needed convincing before BIM adoption was implemented.
	Investment	The business is fully aware of the costs required to implement BIM and fully committed. The businesses aimed to achieve 100% BIM Projects and all staff eventually trained.
	Using BIM	The business has a short, medium and long term strategy in place with BIM Implementation plans. This includes training and using BIM on site.
Client Demand	Using BIM	The demand from clients to use BIM on projects is still low, and a client understanding of BIM is limited. If BIM is requested by a client, the general term is used and specific project requirements are not detailed.
Government Strategy	Competency	The pilot project has enabled the company to ensure skills necessary to meet the Governments requirements exist within the company and associated consultants, and the company is now looking at the future to be ready when Level 3 BIM will be used in the industry.
Staff training	Investment	The company is committed to training staff. Although they are concerned about staff willingness to change working ways and the cultural change BIM will bring. The next step for the company will be wider communication of BIM throughout the business.
Legal implications	Documentation	The business plans to eventually include BIM deliverables in all future contracts. Contracts will be updated and all associated documentation to include BIM specifics and meet guidelines outlined in the CIC documents.
	Competency	Legalities on the model ownership, the business have used the CIC document guidelines that an output from the model will be a deliverable. Therefore an output is the same as a traditional piece of information produced; the consultant creating it, is responsible for it. However the lead designer will be responsible for the whole design, as they co-ordinate it.
Technology Capabilities	Using BIM	The software used in the pilot project showed many benefits, although the business needed to adapt methods to get out of the software what it required. The output of BIM needs to be established before commencing a project, so a BIM can be created for specific outcomes required. The uniqueness of each project means BIM requirements will change. Therefore the definition of BIM for that project needs to be established, so the correct method, software, consultants can be chosen. The company believes the input and guidance from the team that have gone through the process will be able to establish these requirements.

Documentation	A series of documentation containing all the lessons learnt from using the software, and producing a model will be produced. These lessons will be written into guidelines, and rules for the company to produce internal modelling rules and BIM strategies.

5. LESSONS LEARNED AND RECOMMENDATIONS

In the case study, problems were overcome and solutions developed, by a dedicated team, which went through a huge learning curve and cultural change, proving the success with BIM has direct relationship with the user's level of determination to succeed. Therefore choosing the right leaders to implement BIM and become experts in this field is vital.

The BIM team developed procedures and processes from first principles which has shown a truly holistic approach and in doing so identified all the benefits and best practices to be capitalised upon as well as the potential risks to avoid.

This case study also sought views of BIM implementation from all stakeholder perspectives, not only developing an understanding directly from a Contractors' perspective but also from that of the consultant and client. This enabled the contractor to proactively contribute to all stages of the BIM process and constructively challenge developments as the project progress.

One of the major sources of error in the BIM model creation on the pilot project was the introduction of inconsistent information, by different consultants and different individuals. The recommendations on modelling and other implementation variables will be used to produce a robust set of rules and standards, defining the way in which modelling should be undertaken. This can then be clearly communicated to all consultants in the form of the BIM Standard as well as the project specific BIM Execution Plan, which is collaboratively populated by the whole design team to ensure consistency, commitment and buy-in. These two documents combined then provide the backbone to the implementation of a successful BIM Project.

The decision of if, how, and when to use BIM on a project should be one of the key considerations in the initial project planning phases. The decision on whether to use BIM depends on various considerations, such as project delivery method, project schedule and cost, etc. The observations and evaluation of the BIM adoption processes in the case study suggest that a medium (regional) to small contractor should consider a number of points to successfully implement BIM, which are summarised as following.

1. Commitment and buy in from all people responsible in the implementation.
2. Identify BIM Co-ordinator for each project and BIM Champions from different disciplines to lead the process and become a conduit for the lessons learnt.
3. Identify what project BIM will firstly take place on - ie a pilot project with self-developed BIM or provided by consultants BIM model through tender or later stages of the project.
4. Ensure a willingness of team to share information, work collaboratively and integrate design with construction at project level.
5. Understand BIM functionalities and software and keep up to date with standards and code of practices.
6. Understand the maturity wedge to understand what level the business is currently working at and agree the level the business would like to achieve.
7. Train BIM champions. Training is needed to effectively implement BIM technologies. Produce a training plan for the future.
8. Communicate through the business: what has been established and what will happen, what are the business' objectives.
9. Produce a company strategy / standard document to define the standards, settings and best practices and level of details required in the model.
10. Establish best practises including guidelines for internal and external collaborative working.
11. Produce a project BIM Execution plan, detailing clear deliverables for the project and clear ownership of model elements through the life of the project.
12. Train staff on BIM, department by department (for the required function).
13. Audit processes to be put in place on projects and identify someone to audit BIM use.

As various software are required to achieve integrated BIM model, a collaborative document control system, which is also backed up by the BIM task group (HM Government, Department for business innovation & skills, 2012), was seen as essential to manage design changes and any other updates to the models and to enable collaborative working and culture.

6. CONCLUSIONS

In the case study project, creation of co-ordinated BIM was found to be labour intensive at the early stages of the project where lots of learning is required. A large number of object creation was required in the modelling process. However once a library of objects have been created (or is available for use), this will reduce the time in the modelling process in future projects as the objects can be reused and refined. It was identified that a series of documents establishing rules and guidelines for model creation, integration and management are required. The objective of such documents will be to ensure that the model is developed in a manner that allows the collaborative approach to continue to be used, and for the model to be fit for purpose. The study also identified that for successful implementation of BIM, it is crucial to have understanding of and follow standards such as AEC Industry standard and PAS 1192-2 and also produce a BIM Strategy Document and Project Execution Plan specific to the company requirements.

The interview reinforced the importance of senior management's commitment to BIM, and significance of developing own BIM strategy, processes and standards. This study also reiterated the need for staff training and a cultural change in the business as identified in the literature. The learning of BIM functionalities by carrying out a pilot project has helped the company to develop understanding of BIM and knowledge to use BIM in future projects. The use of MEP consultant's BIM model in the pilot project highlighted that the team needed to learn skills on the use of software to run what if scenarios and after the learning, the team were able to review high level buildability and evaluate the consultants design. This enabled the contractor to proactively contribute to the improvement of design. It is envisaged that the investment made in the pilot project would enable the company to win work and to be in the forefront of other competitors.

7. REFERENCES

AEC UK. (2012,). AEC (UK) BIM Protocols., from AEC (UK) CAD & BIM Standards [online] http://aecuk.wordpress.com , Accessed on October 02, 2012.

BIM Technologies Alliance (2012). *National BIM Library*. [online] http://www.nationalbimlibrary.com/ Accessed on March 05, 2013.

Cabinet office. (2011*). Government Construction Strategy*. London: Cabinet Office.

Construction Users Round Table (CURT, 2010). BIM Implementation: An Owner's Guide to Getting Started. American Institute of Architects. [online] http://www.aia.org/aiaucmp/groups/aia/documents/pdf/aiab085571.pdf Accessed March 16, 2013

Department of Business, Innovation and Skills (2011). *A report for the Government Construction Client Group Building Information Modelling (BIM).* Working Party Strategy Paper. London:

Eastman, C. M., Teicholz, P., Sacks, R., & Liston, K. (2008). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers*. Georgia: Wiley.

Epstein, E. (2012). *Implementing Successful Building Information Modeling*. Norwood: Library of Congress.

HM Government, Department for business innnovation & skills. (2012). Building Information Modelling (BIM) Task Group [online] http://www.bimtaskgroup.org/. Accessed October 03, 2012.

McGraw-Hill Construction. (2009). *SmartMarket Report:The Business Value of BIM. America*.

National Federation of Builders. (2012). *BIM: ready or not?* West Sussex: CITB.

NBS (2012). *BIM: mapping out the legal issues*
[online] http://www.thenbs.com/topics/bim/articles/bimMappingOutTheLegalIssues.asp Accessed March 16, 2013.

Smith A. S. and Jones A. B. (1994). Published electronically, CONVR Template, *Proceedings of 4th international conference of office systems* (Jones A. B., editor), University of New Brunswick, 213-232.

Waterhouse, R. (2012). *National BIM Report 2012* - Introduction. London: NBS.

Yin, R. K. (2009). Case study research: Design and methods. 4th Ed. Thousand Oaks, CA: Sage.

Appendix 1: Interview Questions

Q1: How did the business decide BIM should be implemented and why?

Q2: Was BIM being used before?

Q3: Have clients been requesting BIM?

Q 4: Do you believe the software used was adequate & easy to model with?

Q 5: How does the time used to complete the model compare with traditional methods?

Q 6: Were there any contractual issues seen on this project from using BIM?

Q 7: How can you see BIM will be used to benefit the business?

Q 8: Do you believe the Pilot Project succeeded and met your objectives?

Q 9: What are you short, medium and long term BIM strategies?

Q 10: How much capital was approximately invested to carry out the pilot project?

Q 11:What is your next step in your BIM implementation plan?

Q12:What challenges could arise with BIM being rolled out across the business?

Q13:What key aspects would you recommend for another Regional Contractors to use in BIM implementation?

BUILDING INFORMATION MODELING (BIM) USES AND APPLICATIONS IN PAKISTAN CONSTRUCTION INDUSTRY

Kifayat Hussain
Department of Architecture, COMSATS Institute of Information Technology, Park Road, Chack Shahzad, Islamabad, Pakistan.

Rafiq Choudhry
Civil and Environmental Engineering Department, College of Engineering, King Faisal University, Saudi Arabia.

ABSTRACT: *Building Information Modeling (BIM) is one of the most promising and recent developments in the construction industry. In Pakistan, the studies on BIM in academia and construction industry are not very common. This work has tried to find out the potential for BIM for its use and applications in the construction industry. The objectives of this research were to assess the potential of BIM for its use and applications in designing, coordinating, managing and execution of construction projects, the main reasons to take interest in BIM and the major tasks for which it is considered to be adopted. The methodology of this research was based on a questionnaire survey to collect data. The collected data were analyzed by conducting different statistical procedures to make inferences.*

Results of this survey indicated that there was awareness about BIM technology and its processes among the construction industry stakeholders for better visualization and to increase the capacity of design reviews, constructability analysis, and model based estimation and construction sequencing. Results further indicate that the use of BIM minimizes risk of discrepancies between orthographic views including plan, section, and elevation and provides improvement in preparation of budgeting, cost estimating and scheduling capabilities. Finally, the results of this study provide useful information to clients, consultants, contractors and other stakeholders in the construction industry.

KEYWORDS: *Building Information Modeling (BIM), Questionnaire, Virtual Building Construction, Object-Oriented CAD Systems.*

1. INTRODUCTION

BIM is the development and use of a computer software model to simulate the construction and operation of a facility. The resulting model, a Building Information Model, is a data-rich, object-oriented, intelligent and parametric digital representation of the facility, from which views and data appropriate to various users' needs can be extracted and analyzed to generate information that can be used to make decisions and improve the process of delivering the facility (AGC 2009). Building information modeling is emerging as an innovative way to virtually design and manage projects. Predictability of building performance and operation is greatly improved by adopting BIM (Azhar 2011).

With BIM technology, one or more accurate virtual models of a building are constructed digitally. BIM supports design through phases, allowing better analysis and control than manual processes. When completed, these computer generated models contain precise geometry and data needed to support the construction, fabrication, and procurement activities through which the building is realized (Eastman, Teicholz et al. 2011).

Building Information Modeling (BIM) is one of the most promising developments in the architecture, engineering, and construction (AEC) industries (Eastman, Teicholz et al. 2011). BIM is an emerging tool in the design industry that is used to design and document a project, but is also used as a vehicle to enhance communication among all the project stakeholders (Krygiel and Nies 2008). BIM is a revolutionary technology and process that has quickly transformed the way buildings are conceived, designed, constructed and operated (Hardin 2009).

Citation: Hussain, K. & Choudhry, R. M. (2013). Building information modelling (BIM) uses and applications in Pakistan construction industry. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

In the last 5 years, the concept of Building Information Modeling has gained considerable ground in Pakistan. Most of the medium to large architecture firms in the country have at least a basic understanding of BIM. BIM is understood as a design approach that involves data sharing between consultants involved in building projects. The integration of construction and procurement details, environmental data in BIM or its use in project management or facility management is understood to a lesser degree (Mankani 2009). Nonetheless, there is not much research conducted in the country for BIM potential and its use in the industry. The objective of this research is to assess the potential of BIM for its use and to investigate its applications in designing, coordinating, managing and execution of construction projects.

2. LITERATURE REVIEW

The ability to utilize BIM to virtually construct a building prior to construction of the actual building provides an effective means to check its constructability in the real world and to resolve any uncertainties during the process. This allows for more efficient, better designed structures that limit waste of resources, optimize energy usage, and promote passive design strategies (Bynum, Issa et al. 2012).

Building information modeling (BIM) is the latest generation of object-oriented CAD systems in which all of the intelligent building objects that combine to make up a building design can coexist in a single 'project database' or 'virtual building' that captures everything known about the building. A building information model (in theory) provides a single, logical, consistent source for all information associated with the building (Howell and Batcheler 2005).

BIM has shifted how designers and contractors look at the entire building process from preliminary design, through construction documentation, into actual construction, and even into postconstruction building management. With BIM, you create a parametric 3D model used to autogenerate traditional building abstractions such as plans, sections, elevations, details, and schedules. Drawings are not collections of manually coordinated lines, but interactive representations of the model. Working in a model-based framework guarantees that a change in one view will propagate to all other views of the model. As you shift elements in plan, those changes appear dynamically in elevation and section. If you remove a door from your model, the software simultaneously removes the door from all views and your door schedule is updated (Krygiel and Nies 2008).

The project's design performance can also be better developed with the help of a model. The improved ability to visualize the design proposals in the early project phases greatly aids in the assessment of the spaces and aesthetic finishes of the project. The intent of the designers is more easily and accurately communicated to the other project team members, and adjustments can be made until the design meets the desired goals (Kymmell 2008).

The creation of a virtual 3D project model often consists of multiple efforts by different team members. Either the consultants or the specialty subcontractors (if the model is to be used for fabrication purposes, thus functioning as the shop drawing) will generally model their area of responsibility in the project, so that these individual models may then be combined to show a more complete model of the project. All the parts of this composite model can be coordinated so that any existing conflicts (multiple objects occupying the same space) can be found and resolved. This process is referred to as *clash detection* (Kymmell 2008).

3. RESEARCH METHODOLOGY

After the preliminary study, a detailed literature review was carried out and a number of already developed questionnaire were examined. The specifics of the research survey were developed. Google documents were used to design the online questionnaire for the survey and to collect the data. The link of the questionnaire was sent to construction industry related members via email and by hand where it was required. The email addresses were acquired from the website of Pakistan Engineering Council (PEC), Pakistan Council of Architect and Town Planners (PCATP), and from Institute of Architects Pakistan (IAP) and through personal contacts.

Out of 175 questionnaires sent out, 157 were received. Twenty three (23) incomplete questionnaires were excluded and analysis was carried out on 134 questionnaires. The collected data were analyzed using MS Excel and SPSS. Cronbach's Coefficient Alpha was measured to check the reliability of the collected data and to examine the internal consistency of the items of the questionnaire when research variables were on Likert scale. The Shapiro-Wilk Normality Test was performed to check whether data is parametric or non-parametric i.e. whether it were normally distributed or otherwise. Kruskal-Wallis test was performed to check the differences or similarities in the perception of stakeholders about the research variables. A 5% level of significance was considered to represent statistically significant relationships in the collected data. The multiple choice research variables were analyzed through frequency analysis. The perception level of the respondents to this survey about the research variables was assessed by using the mean score (MS) computed by the following formula (Chan and Kumaraswamy 1996):

$$MS = \frac{\sum(fxs)}{N} \quad (1 \leq MS \geq 5) \qquad (3\text{-}1)$$

Where 's' is score given to each research variable by the respondents and ranges from 1 to 5 when 1 is "Strongly disagree" and 5 is "Strongly agree"; f is frequency of responses to each rating (l-5) for each research variable; and N is total number of responses (134). In addition to the mean score, the five-point scale was transformed to relative importance indices using the relative index ranking technique (Chan and Kumaraswamy 1997; Sambasivan and Soon 2007) to determine the rankings of the research variables and verify the evaluation by mean score.

$$\text{Relative Importance Index (RII)} = \sum w / (A^*N) \qquad (0 \leq RII \geq 1) \qquad (3\text{-}2)$$

$$RII = \left(\frac{1n1+2n2+3n3+4n4+5n5}{(A*N)}\right)$$

Where

w = weighting assigned to each research variable by the respondents having range from 1 to 5

n1 = number of respondents for Strongly disagree

n2 = number of respondents for Disagree

n3 = number of respondents for Not sure

n4 = number of respondents for Agree

n5 = number of respondents for Strongly agree

A= highest weight is 5

N = sample size taken as 134

A random sample for this study was selected from a population of more than 30,000 construction industry establishments registered with Pakistan Engineering Council (PEC 2012). It was fairly a large population and the sample is representative of various construction experts.

4. FINDINGS AND DISCUSSION

This research survey was one of the first steps towards understanding and assessing the BIM use and its applications in the local context for coordinating, communicating and managing the construction projects. The data obtained from this study suggested that BIM is an effective tool and process for improving the delivery process of construction projects.

4.1 Respondent's Profile

The respondents to this survey as indicated in Table 1 were Architects / Designers, Engineers / MEP Consultants, Contractors / Specialty Contractors, Academicians and Developers / Facility Owners with the varied professional experience from I to 20 years or more and they were holding positions in their organizations as Managing Director, Project Director / Manager, Project Architect / Engineer / Planner, Contract Manager, Site Manager, Site Supervisor, Facility Manager, and Professor / Lecturer in Academia.

Figure 1 and 2 shows there was an increasing level of awareness about BIM technology and its processes. 88.1 % of the respondents were having either little or general knowledge and 11.2% were with working knowledge of BIM. Most of them (64.9%) have no working experience with BIM (because of varied adoption barriers) but quite a number of them (35.1%) were having varied experience with this technology. However, all of them were having the knowledge of this technology and its processes (the recorded level of knowledge about BIM was 44% for little, 44% for general and 11.2% for working).

Table 1: Respondent's grouping

CI Stakeholders	Frequency	Percent	Cumulative Percent
Architects / Designers	30	22.4	22.4
Engineers /MEP Consultants	48	35.8	58.2
General / Specialty Contractors	25	18.7	76.9
Academician	20	14.9	91.8
Developers / Facility owners	11	8.2	100.0
Total	**134**	**100.0**	

The intention of getting respondents' profile was to establish that the respondents were qualified to respond this survey with varied professional experience in construction industry and working knowledge or experience with BIM.

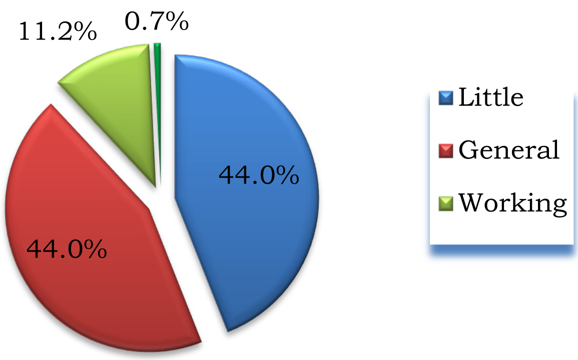


Fig. 1: Respondent's level of knowledge about BIM

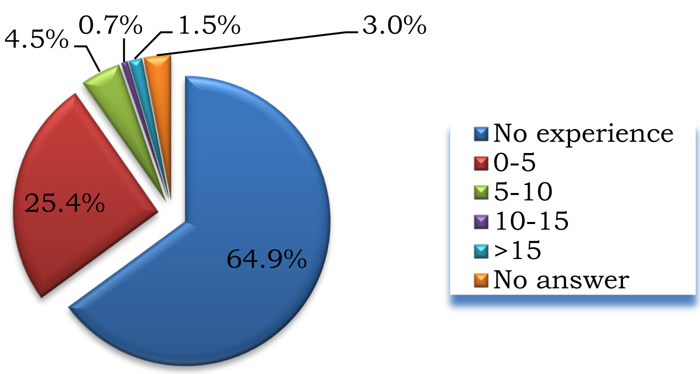


Fig. 2: Respondent's experience with BIM

4.2 Respondent's Organization Profile

The type of the Organizations participated in this survey were Architecture / Designers, Engineers / MEP Consultants, General / Specialty Contractors, Academic Institutions, and Developers / Facility Owners. The geographical location of the projects undertaken by the respondent's Organization was across the country (31% in Punjab, 15.1% in Khyber Pakhtunkhwa, 17% in Sind, 10.1% in Balochistan, 9.9% in Kashmir, and 8.5% in Gilgit Baltistan, whereas some were also working in abroad and having 8.5%). The average number of employees was from 25 to more than 500. The financial strength in terms of the projects undertaken was from 100 to more than 500 million and the type of the projects undertaken by these Organizations were residential, commercial, educational, healthcare, institutional, civil and cultural, industrial, hospitality, entertainment and sports, transportation, religious etc. The intent of getting organization profile was to make sure that the respondents were working in well-established organizations working in different parts of the country on different kind of projects.

4.3 Nature of the collected data

The validity of the collected data was measured and it was found the *p*-values for each research variable was less than 0.05 or 0.01. The correlation coefficient of each research variable was positive and significant at $\alpha = 0.01$ or $\alpha = 0.05$. Cronbach's Coefficient Alpha value was 0.817 and this value reflected a higher degree of internal consistency of the collected data. After conducting the normality test, the significance values were found 0.000 which were less than 0.05 indicating that the collected data was not normally distributed or the data was non-parametric in nature and non-parametric tests were required for further analysis.

4.4 Kruskal-Wallis test

Table 2 shows the outcomes of Kruskal-Wallis test conducted to compare the outcome of the research variables and no significant difference (as $p > 0.05$) was found among the construction industry stakeholders from each other indicating that all have similar general perception about the variables.

Table 2: Kruskal-Wallis Test for Potential for use of BIM

Research Variable	Chi-Square	df	Asymp. Sig.
BIM minimizes risk of discrepancies between plan, section, and elevation.	3.661	4	0.454
BIM facilitates the instant generation of new sections, elevations and 3D views.	4.973	4	0.29
BIM reduces time for drafting and increases for design.	1.292	4	0.863
BIM carries its ability to let AEC people (at different locations) work on the same building model at the same time.	3.735	4	0.443
BIM is connecting AEC people professionally in a new way by sharing the data in an integrated 3D environment for better decision making and project control.	6.997	4	0.136
BIM is efficient for site analysis, site utilization planning and to model the existing site conditions.	5.316	4	0.256
BIM reduces rework in building performance analysis (energy, thermal, acoustic, lighting and airflow).	4.331	4	0.363
BIM is also efficient in structural, mechanical and other Eng. Analyses.	2.883	4	0.578
BIM facilitates in reviewing building codes, bye laws, fire and life safety compliance in 3D environment.	3.572	4	0.467

a. Kruskal Wallis Test

b. Grouping Variable: Construction Industry Stakeholders

4.5 Frequency Analysis

Descriptive Statistics were used for frequency analysis of the research questions to draw the results. The following were the outcomes from this frequency analysis:

Autodesk Revit was being considered to be used in majority (54.4%) of the respondent's Organizations as a BIM application followed by Graphisoft ArchiCAD (7.4%) and the rest were considering or going to test the other applications. This indicated that Autodesk Revit was known to the majority of the respondents to be used as a BIM application. This may be due to the fact that most of the organizations were using Autodesk AutoCAD as 2D CAD application in their offices.

Figure 3 indicates the majority of the Organizations were Planning to adopt BIM in near future (46.3%) followed by the ones which were in the process 'For testing purpose' (29.1%). Also 22.4% were perusing its adoption 'Actively' whereas 2.2% 'Exclusively'. This shows the increasing awareness about BIM and the trend of its adoption in near future by most of the organizations.

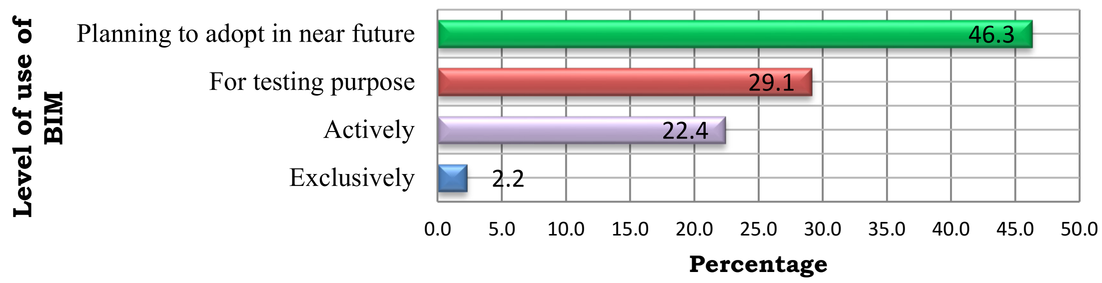


Fig. 3: The level of BIM to be used in the organizations

In response to two the multiple choice questions 'For better visualization and being an interactive tool', followed by 'To increase the capacity of design reviews', were the main reasons to take interest in the BIM applications as shown in Figure 4 whereas Figure 5 indicated 'Constructability analysis' followed by 'Model based estimation and construction sequencing' were the major anticipated tasks for which BIM is being considered to be adopted.

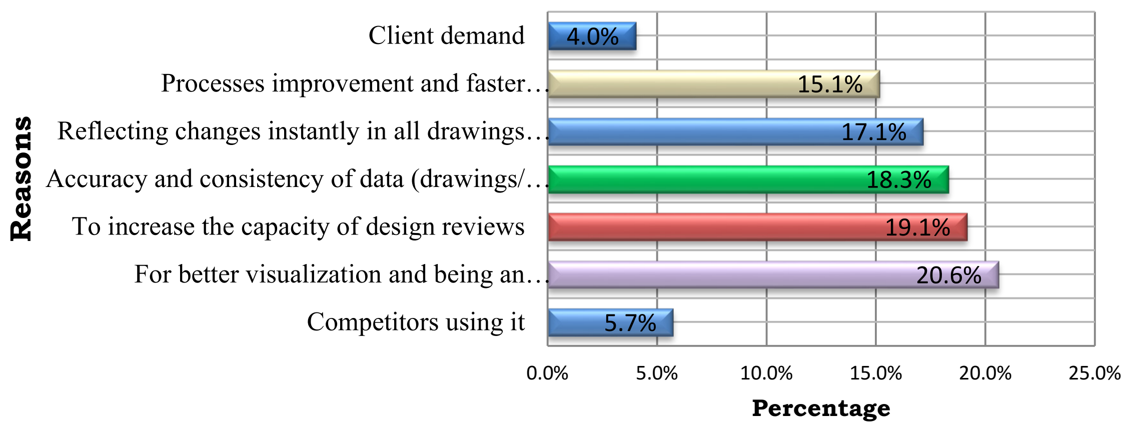


Fig. 4: The reasons for taking interest in BIM applications

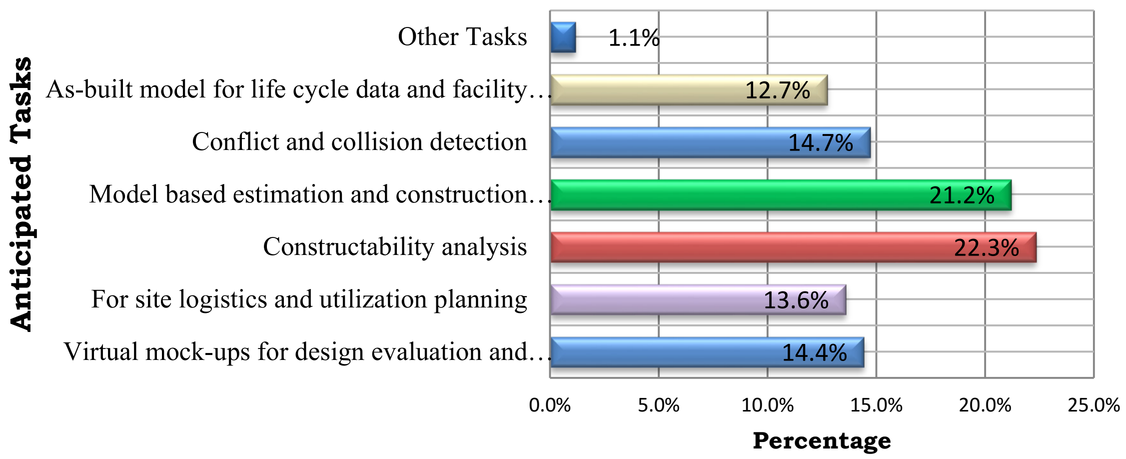


Fig. 5: The anticipated tasks for which BIM is to be adopted

With increasing interest in BIM use and its applications a set of research variables was developed in the questionnaire. The results of the responses to these variables have been shown in in Table 3. The Mean Score (MS) values of these variables indicated that the respondents to this survey were agreed that BIM minimizes risk of discrepancies between plan, section, and elevation, BIM facilitates the instant generation of new sections, elevations and 3D views, BIM reduces time for drafting and increases for design, BIM carries its ability to let AEC people (at different locations) work on the same building model at the same time, BIM is connecting AEC people professionally in a new way by sharing the data in an integrated 3D environment for better decision making and project control, BIM is efficient for site analysis, site utilization planning and to model the existing site conditions, BIM reduces rework in building performance analysis (energy, thermal, acoustic, lighting and airflow), BIM is also efficient in structural, mechanical and other Eng. Analyses, and BIM facilitates in reviewing building codes, bye laws, fire and life safety compliance in 3D environment.

Table 3: Frequency Analysis for use of BIM and its applications

		1	2	3	4	5
Research Variables	MS	Strongly Disagree	Disagree	Not sure	Agree	Strongly Agree
BIM minimizes risk of discrepancies between plan, section, and elevation.	3.94	1	3	23	83	24
BIM facilitates the instant generation of new sections, elevations and 3D views.	3.93	0	3	24	86	21
BIM reduces time for drafting and increases for design.	3.75	0	7	41	65	21
BIM carries its ability to let AEC people (at different locations) work on the same building model at the same time.	3.74	0	5	41	72	16
BIM is connecting AEC people professionally in a new way by sharing the data in an integrated 3D environment for better decision making and project control.	3.81	0	4	37	73	20
BIM is efficient for site analysis, site utilization planning and to model the existing site conditions.	3.74	0	6	40	71	17

BIM reduces rework in building performance analysis (energy, thermal, acoustic, lighting and airflow).	3.75	0	5	39	74	16
BIM is also efficient in structural, mechanical and other Eng. Analyses.	3.83	1	0	38	77	18
BIM facilitates in reviewing building codes, bye laws, fire and life safety compliance in 3D environment.	3.69	1	3	49	65	16

4.6 Ranking of Research Variables

Table 4 shows that when the research variables were ranked through Mean Score (MS) and Relative Importance Index (RII) the following was the outcome:

1. Architects / Designers have ranked '*BIM minimizes risk of discrepancies between plan, section, and elevation*' at the top whereas
2. Engineers / MEP Consultants have ranked
    - '*BIM is efficient for site analysis, site utilization planning and to model the existing site conditions*' and
    - '*BIM is also efficient in structural, mechanical and other Eng. Analyses*' at the top.
3. General / Specialty Contractors have ranked '*BIM facilitates the instant generation of new sections, elevations and 3D views'* at the top.
4. Academicians have marked:
    - '*BIM reduces time for drafting and increases for design',*
    - '*BIM carries its ability to let AEC people (at different locations) work on the same building model at the same time',*
    - *'BIM reduces rework in building performance analysis (energy, thermal, acoustic, lighting and airflow)',* and
    - *'BIM is connecting AEC people professionally in a new way by sharing the data in an integrated 3D environment for better decision making and project control'*, at the highest rank whereas
5. Developers / Facility Owners have ranked '*BIM facilitates in reviewing building codes, bye laws, fire and life safety compliance in 3D environment*' at the top

Table 4: Comparison of ranks for BIM use and its applications

Research Variable	**CI Stakeholders**	**Mean Score**	**RII**	**Overall Rank**
	Architects / Designers	4.0667	0.8133	1

BIM minimizes risk of discrepancies between plan, section, and elevation.	Engineers / MEP Consultants	3.9167	0.7833	4
	General / Specialty Contractors	3.9200	0.7840	3
	Academician	3.9500	0.7900	2
	Developers / Facility owners	3.7273	0.7455	5
BIM facilitates the instant generation of new sections, elevations and 3D views.	Architects / Designers	4.0333	0.8067	2
	Engineers / MEP Consultants	3.9167	0.7833	3
	General / Specialty Contractors	4.0400	0.8080	1
	Academician	3.9000	0.7800	4
	Developers / Facility owners	3.5455	0.7091	5
BIM reduces time for drafting and increases for design.	Architects / Designers	3.6000	0.7200	5
	Engineers / MEP Consultants	3.7708	0.7542	3
	General / Specialty Contractors	3.8000	0.7600	2
	Academician	3.8500	0.7700	1
	Developers / Facility owners	3.7273	0.7455	4
BIM carries its ability to let AEC people (at different locations) work on the same building model at the same time.	Architects / Designers	3.7333	0.7467	3
	Engineers / MEP Consultants	3.8125	0.7625	2
	General / Specialty Contractors	3.5600	0.7120	5
	Academician	3.8500	0.7700	1
	Developers / Facility owners	3.6364	0.7273	4
BIM is connecting AEC people professionally in a new way by sharing the data in an integrated 3D environment for better decision making and project control.	Architects / Designers	3.8667	0.7733	2
	Engineers / MEP Consultants	3.8333	0.7667	3
	General / Specialty Contractors	3.6000	0.7200	4
	Academician	4.1000	0.8200	1
	Developers / Facility owners	3.5455	0.7091	5
BIM is efficient for site analysis, site utilization planning and to model the existing site conditions.	Architects / Designers	3.7000	0.7400	3
	Engineers / MEP Consultants	3.9167	0.7833	1
	General / Specialty Contractors	3.5200	0.7040	5
	Academician	3.6000	0.7200	4
	Developers / Facility owners	3.8182	0.7636	2
BIM reduces rework in building performance analysis (energy, thermal,	Architects / Designers	3.7000	0.7400	4
	Engineers / MEP Consultants	3.8333	0.7667	2
	General / Specialty Contractors	3.5600	0.7120	5

acoustic, lighting and airflow).	Academician	3.9000	0.7800	1
	Developers / Facility owners	3.7273	0.7455	3
BIM is also efficient in structural, mechanical and other Eng. Analyses.	Architects / Designers	3.8000	0.7600	3
	Engineers / MEP Consultants	3.9167	0.7833	1
	General / Specialty Contractors	3.8000	0.7600	3
	Academician	3.6500	0.7300	4
	Developers / Facility owners	3.9091	0.7818	2
BIM facilitates in reviewing building codes, bye laws, and fire and life safety compliance in 3D environment.	Architects / Designers	3.7333	0.7467	3
	Engineers / MEP Consultants	3.7500	0.7500	2
	General / Specialty Contractors	3.6400	0.7280	4
	Academician	3.4500	0.6900	5
	Developers / Facility owners	3.8182	0.7636	1

This ranking (as shown in Table 4) reflected how BIM was perceived by different construction industry stakeholders according to their interest in BIM use and its applications. Architects / Designers were more interested to use BIM to minimize risk of discrepancies between plan, section, and elevation whereas Engineers / MEP Consultants have indicated to apply BIM for site analysis, site utilization planning and to model the existing site conditions and to use BIM for Engineering Analyses. General / Specialty Contractors have the perception that BIM facilitates the instant generation of new sections, elevations and 3D views. This may be due to their interest in generating shop drawings for offsite prefabrication. Academicians were in a view to use BIM to reduce time for drafting and to increase for design and also to reduce rework in building performance analysis. Developers / Facility Owners have thought about BIM that it facilitates in reviewing building codes, bye laws, fire and life safety compliance.

In overall ranking as shown in Figure 6 for use of BIM in the Construction Industry 'BIM minimizes risk of discrepancies between plan, section, and elevation' is ranked at the top and followed by 'BIM facilitates the instant generation of new sections, elevations and 3D views' whereas 'BIM facilitates in reviewing building codes, bye laws, fire and life safety compliance in 3D environment', is ranked at the lowest and followed by 'BIM carries its ability to let AEC people (at different locations) work on the same building model at the same time' and 'BIM is efficient for site analysis, site utilization planning and to model the existing site conditions' both with the same ranking.

This overall ranking indicates that construction industry stakeholders have the perception for use of BIM that it minimizes risk of discrepancies between orthographic views like plan, section, and elevation. They also perceive BIM as a facilitator that instantly generates new sections, elevations and 3D views. They have least perception about BIM that it facilitates in reviewing building codes, bye laws, and fire and life safety compliance in 3D environment. This could be because of most of the industry people as indicated in Fig. 1 and 2 did not have sufficient working experience and knowledge with the BIM technology and its process.

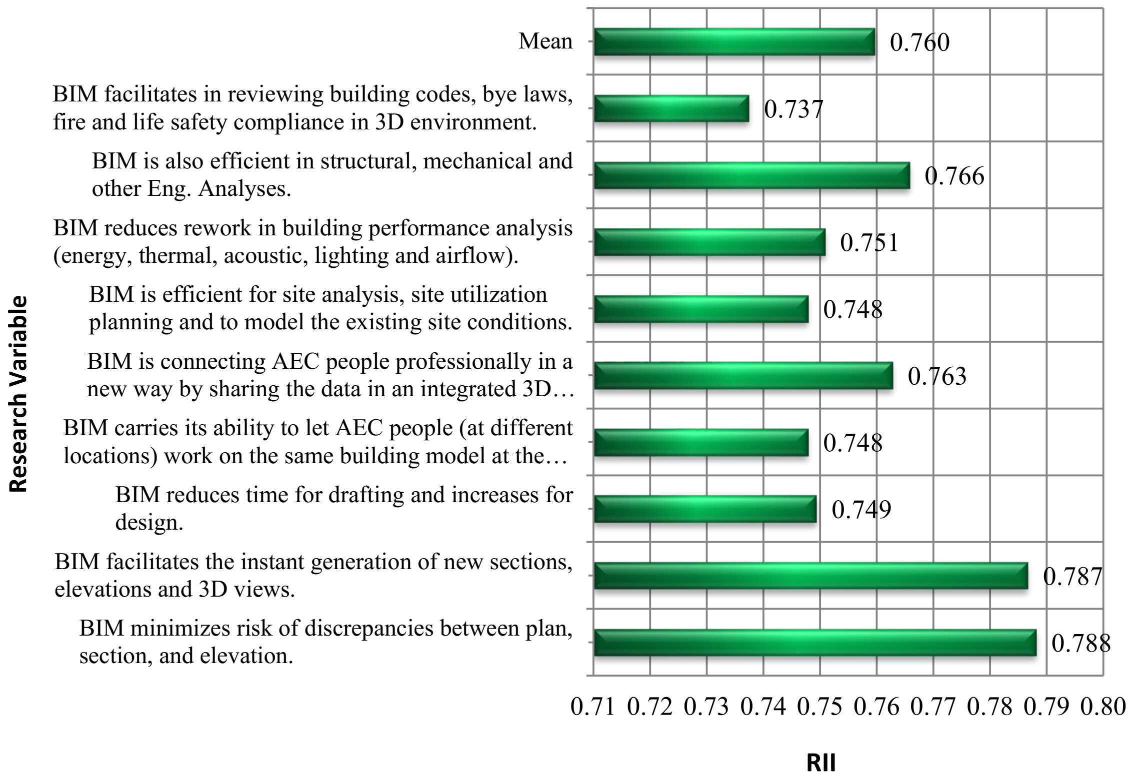


Fig. 6: Overall ranking for Potential for use of BIM

5. CONCLUSIONS

There was an increasing level of awareness about BIM technology and its processes as 88.1 % of the respondents were having either little or general knowledge and 11.2% were with working knowledge of BIM. Majority of the respondents (64.9%) of this survey have no working experience with BIM because of various adoption barriers but quite a number of them (35.1%) were having varied experience with this technology. According to the overall frequency analysis of the collected data 'For better visualization and being an interactive tool', followed by 'To increase the capacity of design reviews', were the main reasons to take interest in the BIM applications. 'Constructability analysis' followed by 'Model based estimation and construction sequencing' were the major anticipated tasks for which BIM is being considered to be adopted. Construction Industry stakeholders have perceived the use of BIM that it minimizes risk of discrepancies between orthographic views like plan, section, and elevation. They also believe BIM as a facilitator that instantly generates new sections, elevations and 3D views.

6. REFERENCES

AGC (2009). The Contractor's Guide to BIM. Las Vegas, Associated General Contractors of America

(AGC) Research Foundation.

Azhar, S. (2011). "Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry." *Leadership and Management in Engineering* **11**(3): 241-252.

Bynum, P., R. R. Issa, et al. (2012). "Building Information Modeling in Support of Sustainable Design and Construction." *Journal of Construction Engineering and Management* **139**(1): 24-34.

Chan, D. W. and M. M. Kumaraswamy (1996). "An evaluation of construction time performance in the building industry." *Building and Environment* **31**(6): 569-578.

Chan, D. W. and M. M. Kumaraswamy (1997). "A comparative study of causes of time overruns in Hong Kong construction projects." *International Journal of Project Management* **15**(1): 55-63.

Eastman, C., P. Teicholz, et al. (2011). BIM Handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors, Wiley.

Hardin, B. (2009). BIM and Construction Mmanagement: proven tools, methods, and workflows, Sybex.

Howell, I. and B. Batcheler (2005). "Building information modeling two years later–huge potential, some success and several limitations." *The Laiserin Letter* **22**.

Krygiel, E. and B. Nies (2008). Green BIM: successful sustainable design with building information modeling, Sybex.

Kymmell, W. (2008). Building information modeling: planning and managing construction projects with 4D CAD and simulations, McGraw Hill Professional.

Mankani, Z. (2009). "Factors Influencing the Growth of BIM in Pakistan." Retrieved May 5, 2013, from http://archpresspk.com/October09_BIM.htm.

PEC (2012). "COMPLETE LIST of all the Constructors/Operators and CONSULTING ENGINEERING FIRMS." Retrieved May 14, 2013, from http://www.pec.org.pk/downloads.aspx.

Sambasivan, M. and Y. W. Soon (2007). "Causes and effects of delays in Malaysian construction industry." *International Journal of Project Management* **25**(5): 517-526.

TOWARDS A SYSTEMATIC PRODUCTION PROGRESS ASSESSMENT BASED ON AR ON BIM – PREREQUISITES AND FUNCTIONAL REQUIREMENTS

João Grazina
Faculty of Science and Technology, Nova University of Lisbon (FCT, UNL)

Nuno Cachadinha
Faculty of Science and Technology, Nova University of Lisbon (FCT, UNL), presently at Technion-Israel Inst. Of Technology

ABSTRACT: *Many studies on augmented reality (AR) have showed that its usage in Architecture, Engineering and Construction (AEC) sector is beneficial. Nowadays AR technology is growing rapidly, and the AEC sector can only benefit from it. Implementing AR upon Building Information Models (BIM) opens perspectives for new techniques and systems to manage onsite production. Measuring activities progress on a worksite is a time consuming process, and sometimes subject to inaccuracy. This may cause delays and cost overrun. Inaccuracy is mainly due to the lack of a standardized method to measure progress, which is usually done by each stakeholder according to his own customary method. Aiming at expediting and improving the reliability of the onsite production progress measurement, this study presents a conceptual model to measure activities progress and perform schedule updating using AR applied to BIM. For this purpose, the systems structure and design methodology (SSADM) was used to gather all the basic operations from similar systems, identify and eliminate the existing gaps, and add new operations. The concept proposed is based on a 5D (3D + schedule + cost) BIM model, which includes the activities planning, linked to the line items from the bill of quantities (BOQ). By superimposing the 5D model with reality onsite, it is possible to measure the activities progress and the cost up-to-date, through a physical comparison of as-built with as-planned. Deviations from the as-planned (both positive and negative) are detected by the system, which then automatically adjusts the planning according to the real worksite situation. This system reduces measurement errors and keeps the activities plan and costs updated. Measuring all kind of operations using AR onsite is seen as future perspectives.*

KEYWORDS: *Building Information Modelling, Augmented Reality, Progress Measurement, Planning Production*

1. INTRODUCTION

The AEC sector is considered one of the poorest sectors in terms of monitoring systems (Navon & Sacks, 2007), thus it is not surprising that delay and costs overruns are common. AEC's productivity tends to be lower than other industries (Park et al., 2012), and 50 to 85% of the problems that construction faces are associated to delayed or missing information sharing (Howell & Ballard, 1996). One of the areas where information sharing systems can significantly improve the sector's efficiency is production and progress measurement.

Onsite production progress measurement consists of periodically measuring the actual progress and comparing it with the expected progress (Kim et al., 2013). This comparison needs to be extremely accurate; otherwise onsite progress control becomes a challenging and ineffective task. Nowadays measurement systems rely on user perception of progress (Golparvar-Fard et al., 2009), which may cause different values of progress for the same activity. For example, a worker informs the project manager that a wall is 90% executed, but on the next day another worker reports a progress of 70%. This difference may trigger the start of another activity that needed 90% completion of the previous one, when the actual progress could be 70%. To prevent these discrepancies from happen, several studies have been made and proved that using systematic approaches which always rely on the same processes and don't depend on user perception is faster and increases accuracy (Navon, 2007).

Due to the amount of information needed to monitor the progress on worksite, BIM models were brought to the scene as a baseline for project controls and are called "as-planned". Those models carry all design drawings and plans in 3D format, activities schedule and costs, thus becoming 5D models. Thus, several possibilities and critical

---

Citation: Grazina, J. & Cachadinha, N. (2013). Towards a systematic production progress assessment based on AR on BIM – prerequisites and functional requirements. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

problems of construction progress assessment using BIM and AR have been explored and discussed. However, this discussion has been mostly centered in the combination of AR with other progress assessment technologies, which still result in complex and costly solutions. A concrete conceptual proposal for progress assessment and schedule update based solely on AR would go further in extracting benefits from AR's simplicity and cost effectiveness.

This study proposes a conceptual platform that utilizes augmented reality (AR) as an information tool to retrieve as-built information, compare it to as-planned and, if needed, reschedule activities and for cost control. Thus this study is driven by the research question "How can AR be used to compare as-planned with as-built, measure onsite production progress and make automatic rescheduling?"

The use of AR sets a new way of comparison, mainly because 3D models can be super-imposed upon the work front reality. This then allows visual comparison between both, which can be made by any stakeholder, regardless of his or her perception of as-built. This approach on measuring onsite production reduces the time spent gathering as-built information and the likelihood of errors.

2. SYSTEMATIC PROGRESS MEASUREMENT

Determining as-built status on a worksite is a very labor intense and time-consuming activity (Navon, 2007). In order to reduce time spent gathering all information of the actual status, several researchers have been working on the use of new technologies and concepts to provide AEC sector with a feasible and faster system to measure as-built status and make an automated progress measurement according to as-built information.

2.1 Technology Review

2.1.1 RFID

Navon and Goldsmidt (2002) proposed Automated-Data-Collection (ADC). This method would be based on Radio-Frequency Identification (RFID) tags and used mostly for monitoring interior finishing activities. The building elements would have a RFID tag attached and the worker would have a RFID reader, which would record information from the tags he would pass by. This data would be downloaded once a day, and based on the time each worker spent on a location, activities progress would be calculated.

2.1.2 Time-Lapsed Images

This technique has been used by several researchers because it can replicate as-built based on photographs taken over the construction time. Golparvar-Fard et al. (2009) has developed a concept called D^{4}AR which uses photographs and videos taken over the time to determine as-built status. This system creates a 3D scenario using advanced programs and algorithms and compares it with the 5D as-planned information.

Zhang et al. (2009) proposed a similar system, which used computer vision to replicate 3D as-built status from 2D images.

2.1.3 Laser Scan

At present date this solution seems the most feasible regarding the accuracy of the collected data. Turkan et al. (2012) used this technology on the construction of the Engineering V Building, University of Waterloo. This technology generates a point cloud with millions of points that creates a 3D scenario of the as-built status. Using 3D object recognition on the point cloud, upon a 3D objects database, these authors achieved an average 96% accuracy match on object recognition.

Using the same technology on a four-floor concrete building in South Korea, Kim et al. (2013) achieved 99% average accuracy on as-built status recognition.

2.1.4 Augmented Reality

Since 2005, AR has been progressively introduced into the AEC sector in number of scenarios. Its main strength is the easiness it offers in representing objects, processes or projects over the real world, thus greatly facilitating user understanding.

Using accurate location devices, such as Global Positioning System (GPS), this technology can impose a 3D project model over a terrain on the exact coordinates. The ability of having a 3D image imposed on real world opens several options for project monitoring, since virtually anything can be imposed, like comments or pictures. The construction site can be designed on a laptop and then be superimposed upon reality in order to detect possible hindrances to beginning construction, thus saving time and money. Comparison made between conventional methods and AR have shown that the latter can greatly increase performance (Lee & Akin, 2011).

2.2 Comparative assessment

The present systems to retrieve as-built information have several limitations depending on the method used.

Using RFID markers is a simple and cheap solution. However the process of gathering as-built information requires all elements to have a marker imbedded, and that marker would have to be read every day.

Time-Lapsed Images method can be considered cost-effective and practical, but have several uncontrollable constrains, such as the weather. Images and videos can be blurry in rainy or foggy weather, and shadows and occlusions from cranes, stairs and formwork can occur. Another concern when using this method is the storage needed to save all the necessary photos and videos (Golparvar-Fard et al., 2009).

Even though the laser-scan methods has proven to be one of the most effective in gathering as-built status, it has several constrains. The equipment should only be handled by people with expertise, it is weather sensitive, which may cause deviations from the desired calibration, it needs an extended objects' database to recognize and match them over the point cloud and the hardware is costly (Markley et al., 2008). This technology requires several scans from different angles to build a complete as-built 3D scenario, thus making it time consuming and subject to human error.

AR is increasingly present in every day's life and it's a matter of time until utilization will become common in construction. Current trends indicate that this technology will be available for any person at any time, and an example of this is Google's new technology "Project Glass" (Google, 2013), which sold as soon as it got to the market. ARCchart, a London-based research firm, forecasts that by 2015 1.6 billion phones on the market will be AR-able. The same study also predicts that the revenue from AR apps will be around 1.7 billion euros for the next two years (ARCchart, 2010)

In the specific field of construction, studies identified a number of areas of application and benefits, such as, visualization aid, architectural assembly guidance and infrastructure tasks (Shin & Dunston, 2008).

2.3 Why AR?

The publication of AR articles has increased in the past few years, especially for construction purposes. Since 1999, 20 articles were published in Automation In Construction (AiC), Journal of Information Technology in Construction (ITCON) and ASCE Journal of Construction Engineering and Management (JCEM) about the use of AR in construction phase (31% of the total articles published about AR in project phases). Also 29 articles, which correspond to 45% from the total analyzed, were about the use of AR for visualization and demonstration phase (Rankouhi & Waugh, 2012).AR's potential for visualization and demonstration can now be considered consensual among researchers.

Wang et al. (2012) proposed a conceptual framework for integrating BIM and AR covering several project stages, including preparation & start-up, transformation of and by resources, monitoring and close down. Also VTT Technical Research Centre of Finland have developed a system which merges AR on BIM called Augmented Reality 4 Building Construction (AR4BC), which was more focused on visualization and merge 3D BIM models on reality (VTT, 2010).

Laser-scan or time-lapsed images are solutions with a high technical component, which require specialized knowledge. These technologies are also costly and complex, when compared with AR solutions. AR's unique feature vis-à-vis previous technologies is the ease of use and visualization. Users can see the construction even before it begins, checking for any constraints or clashes with objects on the work site. AR provides a simple way to enhance user perception of the project, providing visual information imposed on real world helping the user to visually compare elements to gather construction progress. As this technology would be able to use in a portable device, it's ease/precision ratio of gathering as-built would be greatly improved when compared with other available technologies.

2.4 BIM through AR

BIM technology complements AR views ability. BIM models can be viewed by layers or filters, facilitating the progress measure. On the measure process the user could define, for example, “Structure” filter and the 3D BIM model superimpose via AR would only show the elements included on “Structure”, instead of showing all elements. For this to happen it’s proposed a database presented on chapter 5, with a detailed Work Breakdown Structure (WBS) to divide the BIM model as much as it’s needed, so the user can measure all elements without any difficulty. By superimposing differentiated information, selected by the user, through AR, withdrawn from BIM model, the onsite measure process becomes easier and less confusing, reducing the user’s visualization to he’s needs. Wang et al. (2013) identified numerous opportunities for AR in AEC sector, among them AR portable devices, and stated that this kind of technology is expected to be further utilized in the AEC fields and will enhance productivity, safety and efficiency.

3. METHODOLOGY

In order to gain insight and progress towards the proposal of the new conceptual system envisaged, the Structured Systems Analysis and Design Methodology (SSADM) is used. This method, commonly used in systems development, provides a structured path towards clarifying the system analyzed, with data-flow diagrams and text. SSADM has 7 different stages (Schumacher, 2002):

- Stage 0 – Feasibility Study
- Stage 1 – Investigation of Current Environment
- Stage 2 – Business System Options
- Stage 3 – Definition of Requirements
- Stage 4 – Technical Systems Options
- Stage 5 – Logical Systems
- Stage 6 – Physical Design

Advancing to the next stage is only possible after the previous one is completed, thus reducing the possibility of errors. Although this waterfall methodology may take longer than similar systems approach methodologies, it improves productivity, flexibility, takes into account the user’s needs and reduces the cost of re-implementing a new system, due to the ability of structuring processes (Officer, 2012). By analyzing each stage requirements, define connections between processes and limitations, it’s proposed a new method to implement AR on BIM models to measure worksite production progress.

4. REQUISITES FOR A PLATFORM BASED ON BIM THROUGH AR

4.1 Business System Options

This stage describes the platform proposed on this study and portrays the solutions found for the shortcomings identified in the previous stage, as part of the new system proposed.

The method proposed begins with 3D BIM modeling of the construction site. The use of BIM allows the project manager to have all the information regarding the construction elements in a single file, which will reduce the time spent analyzing all shop drawings. In addition, a schedule of all activities should be done according to the bill of quantities and its specifications. It is of major importance that schedule and BOQ are linked, as this allows the measurement of activities and overall cost at any time, based on the current schedule. Integrating the 3D BIM model, schedule and BOQ allows the project manager to have much more control over the project.

Once all the connections between the BIM model, the schedule’s activities and the BOQ are established, the next step is to choose a suitable technology to retrieve the as-built status. This study proposes the use of AR technology to obtain the as-built status by superimposing a 3D model over the worksite scenario. The Intelligent Global Positioning System (iGPS) is proposed to acquire user and model location accurately. This technology is based on the local replication of satellite triangulation. Thus, it is not conditioned by direct line of sight to orbiting satellites, and can be used indoors with a precision of less than 1mm (Berlo et al., 2009). This technology still has some limitations regarding the quantity of transmitters and receivers needed, which make its portability less straightforward. However, it is foreseeable that in a near future these will be overcome. Using this technology the 3D model can be super-imposed on the exact coordinates and scaled to the user position, in order to achieve a match between all 3D model elements and their equivalents in reality, thus allowing for an

Fig. 1: Setting as built status

accurate visual comparison by the operator. This overlap can be done through a portable device, like an iPad, smartphone or a laptop, and the comparison can be done by physical interaction with the screen. Matching the real elements is particularly important, thus the model would have to be on exact scale. This will allow the user to identify as-built status by clicking on the screen over the actual element progress (Figure 1). As the user sets an as-built status, the model automatically calculates the percentage concluded of the activity associated to that element, checks if it is within schedule and, if necessary, readjusts the schedule to match the as-built. The interaction between as-built and as-planned schedule will prevent the start of upcoming activities that require previous activities completion, and will keep the schedule up-to-date. This will avoid making-do, one of the major reasons for waste in construction. Koskela (Koskela, 2000) identified this cause for waste and described it as starting one activity without having all necessary means and requisites available for its continuous execution and conclusion.

4.2 Definition of Requirements

As mentioned before, it is of major importance that BIM models, BOQ and activities schedule are linked. Figure 2 portrays the overall platform's architecture, displayed as a data-flow diagram. The process starts with 3D BIM modeling of the construction project. Those models are composed by elements that could contain information like suppliers, materials, quantities, costs, etc. By linking each element to his corresponding line in the BOQ, the model is enriched with added information and organization. As all elements are combined with BOQ information, activity schedules can be also attached, thus providing the latter with a start and end date. For the successful establishment of these connections, those elements should have 7 specific parameters associated:

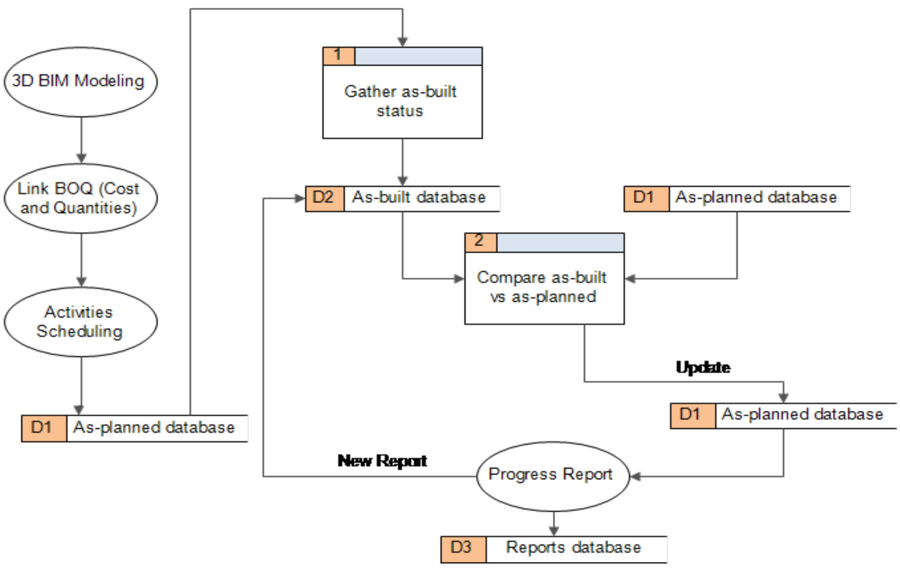


Fig. 2: Platform Architecture

- Material(s)
- Quantity(ies)
- Cost
- Start Date
- Progress
- End Date
- Activity ID

By delivering this information to the “As-planned database”, it becomes easier and faster to see any detail related to the project. That database is cathegorized according to the WBS used on BIM model with a level of detail up to the element.

To gather as-built information this platform needs an accurate GPS system and a software to scale the 3D BIM model to the actual user sight, making possible to set an as-built status by visual comparison (Figure 1).

According to this structure, the user can interact to each of the construction elements and set a progress value. As soon as all under construction elements are assigned a value for their progress, the as-built status can be updated into the “As-built database”. Its only parameter will be the progress of each element, as this is the only parameter needed to compare with the “As-planned database”, shown on Figure 3.

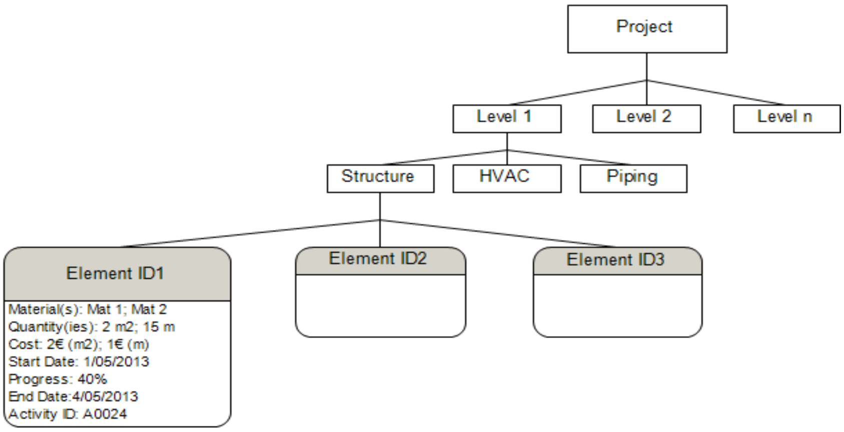


Fig. 3: Database architecture

Each as-built activity progress will be determined based on the average progress of all its elements and their comparison with the as-planned activity progress. For this purpose, each element will be assigned an activity ID. The assumption underlying this comparison is that there is a linear relationship between the time elapsed and the expected percent concluded. For instance, a five days activity should be at 20% completion at the end of the first day. If there is an increase or decrease on its assigned resources, or any other change that affects the duration of the activity in progress, the remaining as-planned schedule will be recalculated and readjusted accordingly. As these changes are made, the respective activity and its subsequent ones should have a new Start and End Date, adjusting the schedule to the new conditions and their implications. This platform is based on a dynamic concept of project controls. Unlike tradicional methods, which rely on static baseline views throughout the project, the proposed system utilizes a dynamic schedule view.

The as-built status will be measured by comparison of the visual input obtained by the portable device on site with the elements of the “as-planned” database. If as-built (BDB) and as-planned (BDP) progresses do not match, the as-planned database will automatically readjust the End Date parameter according to the new expected time remaining to the activity’s completion. Thus, the elements’ “Progress” and “End Date” will be updated in the as-planned database. The as-planned schedule will be dynamically readjusted in the remaining activities, in order to reflect reality and avoid starting activities which are not yet ready to be started. This provides the user with a realistic forecast of the works onsite, as the activities’ schedule always reflects reality on the work front. The corresponding process is shown in Figure 4. This process prevents “making-do”, one of the major waste forms found specifically in construction (Koskela, 2004). In order to keep track of the changes that occurred throughout the project, these will be flagged with a visual note added to the respective construction element, indicating a change to the original schedule on it (Figure 5).

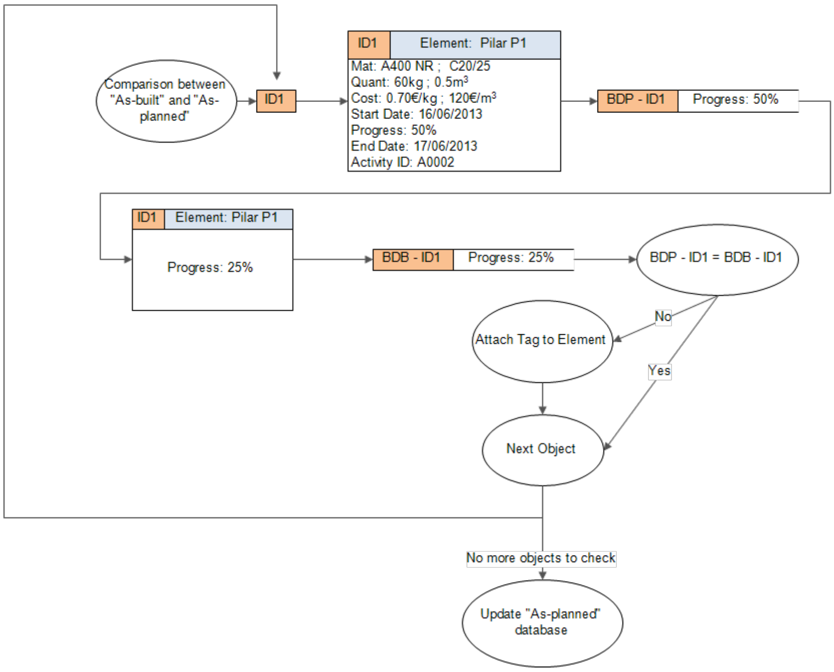


Fig. 4 – Process to compare “as-planned” with “as-built” information

At the end of each as-built information input, a report is produced, which can be customized according to the output envisaged. The elements’ parameterization enables several reports, such as:

- Activities’ Schedule
- Activities’ Cost and Materials used
- Off-Schedule activities
- Overall Progress and Cost

Those reports are then saved in the “Reports database”, which can be accessed any time. The latter will be very similar to the as-planned database WBS. Its first level will be “Date”, in order to enable tracking of project updates, changes and status at any given past time in the project, thus allowing a clear perception of the project’s evolution over time.

Fig. 5: Example of a tag note assigned to a delayed wall with relevant information

4.3 Technical System Options

Using this platform requires a lot of information from the project and a big interaction between 3D BIM model, BOQ and activities' schedule. They are the cornerstones of the proposed platform. Due to the amount of information that is gathered from 3D BIM model, BOQ and activities schedule, this platform will demand a significant involvement in the first stages of the process, as these connections will have to be entered manually. However, once this has been concluded no more big and time consuming inputs will be required. The system will make adjustments and reports based on the quality of the information introduced at this stage, thus it is fundamental that it is carried out meticulously, and all information is introduced correctly.

The system proposed should be mobile and should work effortlessly on smartphones or tablets. This raises the issue of the database storage. In order to avoid importing it to the device, a server client architecture is proposed, where the database is stored at the server and is accessed by the mobile device via wireless network. As-built information gathering will consist of retrieving the AR 3D model from the server and superimposing it to the worksite's images captured by the device's camera, register as-built progress as shown in Figure 1, sending that information via wireless back to the server and finally compare it to the as-planned database.

The user interaction required by this system is very easy, since it is based on visual comparison. This will allow any worker to perform this operation. Specific knowledge is only required to input as-planned information.

5. DISCUSSION OF THE PROPOSED METHOD

The platform presented in this study will expedite project management processes. Project progress is determined faster and more accurately, as it significantly decreases the time spent in gathering as-built status. By creating a database with all reports organized by date, it will be possible to analyze the progress, performance and cost of all activities. This is particularly useful in team meetings, since all information related with onsite works and design is available in a fast and simple way.

The platform proposed aims at low implementation costs. As more and more projects come out in BIM format, it will be increasingly easier to obtain full compatibility. The information required to run the system is part of standard documents in any projects, as it is part of the activities' schedule and of the BOQ. Thus, all the input needed to create "As-planned database" will be available without additional costs. As-built information gathering will be done through equipment of common use, such as laptop computers, smartphones and tablets. This equipment has usually already been acquired by the companies, and its price is significantly lower than other technologic options such as laser scan devices.

Due to its new method of scheduling, this platform provides the user with up-to-date planning anytime throughout the project. In order to always reflect real progress, traditional planning methods must be updated manually and frequently. Otherwise they become obsolete and may trigger wrong decision making. With the dynamic scheduling proposed in this study, stakeholders have a real and accurate perception of the progress, and "making-do" is avoided. Delays or other changes in activities with trigger rescheduling, which will be carried out by changing the as-planned in order to match as-built. As this happens, a tag will be attached to the respective construction element, both visually on the BIM model and on the "Reports Database", in order to keep a record of those changes.

The use of AR seems the way to go in the future and its capacity of providing the user with the exact project model will increase user's perception of the project and decrease the frequency of measurement errors. The proposed platform allows the user to measure onsite progress by marking the actual element's progress on the device, thus avoiding subjective and often inaccurate evaluations of the percent completion of the element.

At its present stage, this platform still has some limitations regarding some types of activities. Earth works are a challenging activity to measure visually. Visual perception may differ from the actual earth moving due to varying depth, and the positioning to measure progress would have to be very specific. Underground or deep interior activities may have problems too, due to the lack of GPS signal. Thus this system is, so far, proposed for structure works, mechanical electrical and plumbing (MEP), heating ventilation and air conditioning (HVAC), tiling and painting.

6. CONCLUSIONS AND PERSPECTIVES

The utilization of AR technology has been proven feasible in AEC sector (Shin & Dunston, 2008). This platform is built upon existing literature by proposing a novel approach to the use of AR for measuring progress, and guarantees schedule relevance and accuracy by utilizing visual comparison between a super-imposed 3D model and the real construction, through AR applied to BIM, for continuously keeping schedules updated. Simultaneously, it keeps track of the schedule changes, through visual flags shown to the user. This addresses the making-do problem, which has been identified as a construction specific type of waste (Koskela, 2004). In addition, this study goes one step further towards developing a progress measurement on the worksite, by proposing a concrete framework that establishes relationships between the construction elements present in the 3D BIM models, the bill of quantities and the activities' schedule.

By importing all BIM elements, provided with 7 parameters to as-planned database, all information regarding construction project is reachable in a few seconds. AR technology was chosen to measure progress because it is fundamentally independent from the user's accurate perception of 2D drawings. Instead a visual approach is proposed by imposing the 3D model over the worksite. As progress of each element is set and recorded on as-built database, then it's compared with as-planned database, checking if any activity is off-schedule. Updating as-built information to as-planned database preserves activities relationships and prevents activities from starting, if any previous one isn't finished. This platform can effectively reduce the amount of measurement errors, as well as increase efficiency by providing visual information to the workers.

The reports database will allow the project manager to monitor every progress detail, such as, costs, activities progress, materials spent, etc., at any given past time of the construction. It's believed that such database will improve management, due to its organization and WBS. As each element has 7 key parameters, it will be possible to measure progress based on different variable and detect flaws or waste patterns by analyzing them.

The authors are now assessing some AR limitations and working on expanding this platform to be suitable to other construction activities, such as earth moving. Positioning is also an important field, which is being looked at. AR can take over significant parts of what is today topography work. It can help the user to determine the exact position of construction elements, with the added value of clarifying what exactly the element will look like, and what will be necessary for its erection. This is a significant step forward from today's topographic marks. Safety activities are also being looked at, in particular choosing the best placement for safety barriers and other collective protection equipment.

7. REFERENCES

ARCchart, 2010. *Mobile Phone Augmented Reality: Markert Analysis and Forecast.*ARCchart

Berlo, L., Helmholt, K. & Hoekstra, W., 2009. *C2B: Augmented Reality On The Construction Site.* 9th International Conference on Construction Applications of Virtual Reality.

Golparvar-Fard, M., Peña-Mora, F., Arboleda, C. & Lee, S., 2009. Visualization of Construction Progress Monitoring with 4D Simulation Model Overlaid on Time-Lapsed Photographs. *Journal of Computing In Civil Engineering,* Volume 23(6), pp. 391-404.

Golparvar-Fard, M., Peña-Mora, F. & Savarese, S., 2009. D4AR – A 4-Dimensional Augmented Reality Model For Automating Construction Progress Monitoring Data Collection, Processing And Comunication. *ITcon,* Volume 14, pp. 129-153.

Google, 2013. *Project Glass.* [Online] Available at: http://www.google.com/glass/start/ [Accessed on 30/4/ 2013].

Howell, G. & Ballard, G., 1996. *Factors Affecting Project Success in the Piping Function.* 3rd Annual Conference of the International Group for Lean Construction.

Kim, C., Son, H. & Kim, C., 2013. Automated construction progress measurement using a 4D building information model and 3D data. *Automation in Construction,* Volume 31, pp. 75-82.

Koskela, L., 2000. *An exploration towards a production theory and its application to construction,* Mastersthesis in Helsinki University of Technology.

Koskela, L., 2004. *Making-do, the eighth category of waste.* 12th Annual Conference of the International Group for Lean Construction.

Lee, S. & Akin, O., 2011. Augmented reality-based computational fieldwork support for equipment operations and maintenance. *Automation in Construction,* 20(4), pp. 338-352.

Markley, J., Stutzman, J. & Harris, E., 2008. *Hybridization of Photogrammetry and Laser Scanning Technology for As-Built 3D CAD Models.* Aerospace Conference IEEE 2008.

Navon, R., 2007. Research in automated measurement of project performance indicators. *Automation in Construction,* Volume 16, pp. 176-188.

Navon, R. & Goldschimdt, E., 2002. Monitoring labor inputs: automated-data-collection model and enabling technologies. *Automation in Construction,* Volume 12, pp. 185-199.

Navon, R. & Sacks, R., 2007. Assessing research issues in Automated Project Performance Control (APPC). *Automation in Construction,* 16(4), pp. 474-484.

Officer, O. G. C. I., 2012. An Introduction to Structured Systems Analysis ¥& Design Methodology (SSADM). *Office of the Government Chief Information Officer - The Government of the Hong Kong Special Administrative Region.*

Park, C.-S., Lee, D.-Y., Kwon, O.-S. & Wang, X., 2012. A Framework for Proactive Construction Defect Management using BIM, Augmented Reality and Ontology-based Data Collection Template. *Automation in Construction,* 33(0), pp. 61-71.

Rankouhi, S. & Waugh, L., 2012. *Augmented Reality Technologies For AEC Projects: A Literature Review.* 12th International Conference on Construction Applications of Virtual Reality.

Schumacher, M., 2002. *The use of SSADM (Structure Systems Analysis and Design Methodology) as a standar methodology on Information Systems Projects.* QB107 Autumn Semester Report 2001-02.

Shin, D. H. & Dunston, P. S., 2008. Identification of application areas for Augmented Reality in industrial construction based on technology suitability. *Automation in Construction,* 17(7), pp. 882-894.

Turkan, Y., Bosche, F., Haas, C. T. & Haas, R., 2012. Automated progress tracking using 4D schedule and 3D sensing technologies. *Automation in Construction,* 22(0), pp. 414-421.

VTT, 2010. [Online] Available at: http://www.youtube.com/watch?v=xpZDXih9zLg [Accessed on 15/05/2013].

Wang, X., Chi, H. & Kang, S., 2013. Research trends and opportunities of augmented reality applications in architecture, engineering, and construction. *Automation in Construction,* Volume 33, pp. 116-122.

Wang, X. et al., 2012. A conceptual framework for integrating building information modeling with augmented reality. *Automation in Construction,* Volume 34, pp. 37-44.

Zhang, X. et al., 2009. Automating progress measurement of construction projects. *Automation in Construction,* Volume 18, pp. 294-301.

AN AUGMENTED REALITY TOOL FOR FACILITATING ON-SITE INTERPRETATION OF 2D CONSTRUCTION DRAWINGS

Stéphane Côté & Philippe Trudel
Bentley Systems, Québec, Canada

Rob Snyder
Bentley Systems, Lexington, KY, USA

Renaud Gervais[2]
Bentley Systems, Québec, QC, Canada

ABSTRACT: *Two-dimensional drawings are the only type of design document that is legally approved for construction. For large construction projects, because of the drawings' high level of abstraction and because of the very large number of drawings, interpretation and correct understanding of drawings is identified by some construction firms as their greatest single challenge. To do the building work as designed, the builder must understand the meaning of the drawings, and this comes from establishing a visual correspondence between the abstract 2D drawings and the physical environment. Unfortunately, that correspondence may not be easy to obtain when the structure of interest is not clearly visible from the user's position (occlusion, differences between the model and the actual building, etc.). In this paper, we propose a technique that enables the display of 2D drawings into the real world using augmented reality in a way that can overcome those kinds of limitations. The tool enables users to "browse" the real world in search of drawings, or to request the real location that a specific drawing represents, and to view each drawing within a context composed of a combination of captured photographic reality and designed virtual modeling. Augmentation is achieved by displaying the drawing using either an animated sliding plane that shows it being "inserted" into the real building, or a clipping technique that displays the drawing inside a clipped 3D model which in turn is inside the real building. The 2 techniques were implemented and tested in a situation where section drawings are visualized from the outside of the building. Our results show that those visualization techniques provide good 3D perception in a representation that is easy to understand visually. They also enable quick localization of the drawing in its environment, and provide a better understanding of the drawing with respect to its context: the 3D model and the built environment.*

KEYWORDS: *Augmented reality, panorama, construction, 2D drawings, design, 3D model.*

1. INTRODUCTION

Construction is a complex process involving a large number of complex tasks aimed at the development of physical infrastructure (the built environment). To ensure that infrastructure is safe for human use, design and construction firms comply with regulation, like building codes, and conduct their work within a legal framework that holds engineers and architects responsible for the communications they issue and certify. In the whole construction process, each team (designers, architects, builders, engineers, surveyors) is legally responsible for their part of the work. For that reason, information between the teams must be transferred in a clear and unambiguous way. Certification helps define the legal bounds of responsibility. For instance, by putting his seal on a drawing, or a set of drawings, an architect asserts and claims his own responsibility and accountability for that statement, or set of statements. Furthermore, drawings, by their nature, contribute to the definition of legal boundaries of responsibility in an essential way that makes certification possible. Because drawings are location-specific, they are finite in number. Because of the finiteness of a set of drawings, describing only representative locations, and only implying the rest of a project, as a practical matter, architects and engineers have adequate control over these representations.

Infrastructure, however, is inherently 3-dimensional. Designers propose a 3D building concept, and ultimately builders create the 3D object that corresponds to the designer's idea. Yet, the only design document that is legally

Citation: Côté, S., Trudel, P., Snyder, R. & Gervais, R. (2013). An augmented reality tool for facilitating on-site interpretation of 2D construction drawings. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

[2] Current affiliation : INRIA, Bordeaux, France.

approved for construction is the 2D drawing. Consequently, even though designers may have produced a 3D model of their design, drawings, because of their location-specific review and certification, are the only form of visual design communication that satisfies the legal framework required for construction. Since the process forces designers, architects and engineers to take one dimension out of their 3D design, drafting consists of a complex set of tasks aimed at accurately representing a 3D object with 2D representations. For large infrastructure projects, the process may lead to the production of a very large number of drawings (e.g. thousands), each one referring to other drawings, through symbols that indicate their relative spatial relationship. The process is complex and must be done with great care, to ensure that when the builders read the drawings, they will be in a position to build the 3D building as it was designed.

Because of the large number of drawings and their high level of abstraction, the transmission of information between the designer and the builder is not easy. Three main difficulties arise from the process:

- Because drawings are 2D representations of a 3D object, and because each drawing refers to several other drawings in the set, by way of special symbols, understanding the meaning of any drawing is a complex task that takes sustained continuous effort from the builder to continually keep and update a mental representation of the project by putting many related drawings together in space, by imagination, and projecting their implied 3-dimensional continuities.
- Drawings are often arranged in groups. This is illustrated in Figure 1, where 4 sections of the same wall are displayed on the same sheet. When building that wall, the builder must therefore carefully select and use the corresponding section of the drawing. Many drawings in a set are similar. The builder must be careful to associate each drawing with its correct actual location in the proposed real environment of the project, its actual location in reality, to build the right things in the right place.
- The builder may not always notice that there is a drawing that represents some physical location of interest in the building, as this would require familiarity with the whole document set, which requires continuous long-term effort and meticulous attention. Consequently, some drawings of the set may inadvertently go unnoticed.

Because of those difficulties, errors can be made, both in the preparation of those drawings and in their interpretation, and in any case, the task of understanding the meaning of the drawings may be said to be more difficult than necessary; that is, visual communication could certainly be made more effective than is provided for today by either of the two conventions, drawing or modeling.

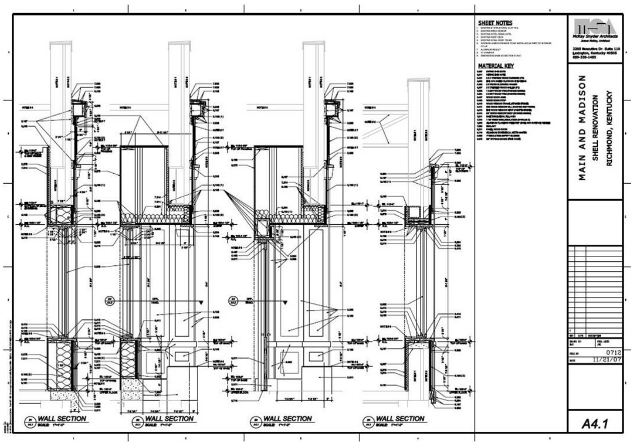


Fig. 1: A typical drawing showing 4 sections of the same wall.

To decrease ambiguity and errors that can be caused by working only with 2D drawings, or with 3D models and 2D drawings separately, a few years ago Bentley® proposed a new concept, commercially released in 2012, and referred to as "Hypermodeling". Using 3D model clipping, 2D drawings are displayed automatically inside the 3D model, on demand, at the exact location they represent (see Figure 2). The spatial relationship between various drawings is then much more clearly represented, as each drawing is graphically represented *in-situ* in a 3D model.

The Hypermodeling technique is very useful for improving communication between designers and builders, as it indicates exactly the location of the certified drawings in the building model and helps both designer and builder more fully, correctly, and quickly understand the meaning of the lines and other graphic elements in each drawing. The technique also helps build trust in a 3D model, because it makes clear the difference between “just any location” (which may or may not be complete enough), and specific locations that are certified as graphically complete enough. Although it is very useful, that solution is not complete for construction, as a builder must still establish a visual correspondence between the 3D model and the real environment of the building. That correspondence, essential for doing his work at the right location, may not be clear when the environment is very different from the model, for instance early in the construction process, when the building is fully built, or when construction material or furniture is in the way.

To address the problems faced by builders to interpret drawings on-site because of their large number and because of the fact that their spatial location is only specified relative to the other drawings in a symbolic and abstract way (within a set of drawings), or virtually (within the hypermodel), what would be needed is a way for the builder to see exactly the correspondence between the certified drawings and the locations they represent in the real environment – in other words, a system that would visually indicate the relationship between a 2D drawing and the 3D real environment. This, we hope, might decrease the number of construction errors caused by drawings misinterpretation, and may save the time it normally takes to search for the right drawing. That problem is an excellent candidate for augmented reality.

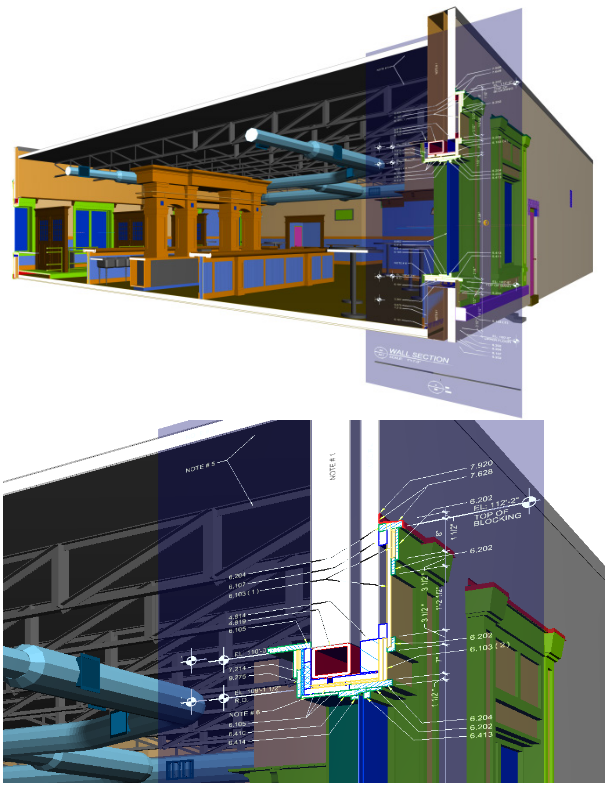


Fig. 2: Two views of a clipped 3D model showing the exact location of a section 2D drawing aligned in place.

In this project, we propose a new visualization technique based on augmented reality (AR) that renders 2D drawings at the exact physical location they represent, in a way that is visually compelling, informative, and helpful for their interpretation, on-site, by construction and maintenance workers.

2. RELATED WORK

The use of 3D CAD building models in an augmented reality context has been studied many times and shows high potential. For instance, Woodward et al (2010) described an AR system aimed at displaying BIMs in their physical world context. Hammad et al. (2002) described a case study in which a bridge inspector visualizes a bridge CAD model based on his location and orientation. In their user evaluation, Olsson et al. (2012) confirmed the usefulness of mobile AR for visualizing urban plans. Golparvar-Fard et al. (2011) described a system for the automated acquisition of point clouds from photos and their use for comparing with 4D BIMs in an augmented environment.

The specific problem we are trying to solve is different, as it is mainly related with spatial perception and 2D drawings. Spatial perception is a fundamental issue in the CAD software industry. In their work, Dunston et al. (2002) discussed the importance of considering spatial cognition issues in the validation of AR CAD systems.

The specific use of 2D CAD drawings in AR was also studied. For instance, the works of Mackay et al. (1995) and Fiorentino et al. (2010) focused on using 2D drawings as an interface to visualize the corresponding 3D model using AR. In our study, our purpose is different: we want to display 2D drawings at the exact location they represent in the 3D world. The works that are conceptually closest to ours are the ones of Navab's team (1999 & 2002) where a floor plan drawing is draped onto the corresponding real floor in an industrial context. However, their study was limited to floor plans, where the physical floor (used as an augmentation surface) is visible during the augmentation session. In another investigation, Gimeno et al. (2011) described an AR system that displays 2D floor plans and elevations overlaid onto live or static images or building floors or facades. In our study, we wanted to focus on drawings that are arbitrarily located in space (e.g. section drawings) and for which the corresponding real world location might not be visible nor represent a good projection surface for augmentation.

Augmentation in the presence of occlusion is a problem that was often explored. For instance, when augmenting a scene with an object that is normally hidden (for instance a cable hidden behind a wall), it is well known that simply overlaying that object on top of the occluding surface (in this case: the wall surface) alters perception (Kalkofen et al., 2007). To display the augmentation at its true location, parts of reality that normally occlude that object must first be hidden, for instance using techniques used for Diminished Reality (DR) (Mann et al., 2001). In this work, we propose a technique inspired from the Magic Lens metaphor (Bier et al., 1994), where the portion of the scene that is removed is replaced by a clipped 3D CAD model, which helps preserving perception.

3. PROPOSED SOLUTION AND RESULTS

The visualization of 2D construction drawings in an AR context is hard. To display the drawing at its exact physical location, a "physical context" is ideally needed to display the drawing into. For instance, a floor plan would be easy to understand in an augmented scene if it were displayed on the surface of an existing physical floor. The floor would, in this case, be used as a context for displaying the drawing. The problem is that on construction sites, the ideal physical context may be invisible, either because it has not been built yet, or because of occlusion by other parts of the building. The main problem is therefore one of perception: how to display a 2D drawing in its physical context when that context is not visible.

To alleviate the problem, we proposed 2 techniques: sliding plane, and model clipping. The 2 techniques are described below.

Since we concentrate on the visualization aspect of the augmentation problem, a simplified augmentation environment was used. The system we used is based on the augmentation of static panoramic images that are used as a representation of reality and captured prior to the augmentation session (Côté, 2011) – this is described as a "fixed configuration" by Lee et al. (2005). The 3D model, used for augmentation or clipping, was aligned with the panoramas at the beginning of the session, using the method described in Poirier's thesis (2011). Used on the field, the augmented scene can be viewed on a portable (tablet) device, that displays the portion of the augmented panorama that corresponds to the user's instantaneous orientation, estimated using an orientation sensor. Used at the office, the remote augmented scene can be viewed on a personal computer and navigated using a mouse. Although this only produces an emulation of AR, it has the advantage of offering jitter-free augmentation, as no live video tracking is involved. Consequently, the system is not very demanding in terms of computing resources. However, it has the disadvantage of providing no real-time augmentation, and is based on images that are, by definition, out of date. Yet, the system is ideal for some types of applications, for instance where accuracy is very important (Côté, 2011), where access is not easy because of distance or safety issues, for preparing site visits, and also very generally in common situations in which authored, instructive, directive, actionable, and certified visual statements are to be well and correctly understood, and where contextualization improves their intelligibility.

In this experiment, all 3D models and drawings were designed by McKay Snyder Architects, James McKay, Architect, using MicroStation®. Panoramic images were obtained from individual photos captured with a standard digital camera and stitched using Microsoft ICE. Augmentation experiments were run on a standard 2-core laptop computer with 2 Gb of RAM. However, since the prototype requires very little CPU power, it could easily be ported to tablet devices. Augmented scenes were viewed using a prototype based on Ogre3D. 2D drawings and clipped models were rendered in MicroStation and imported into the Ogre3D application as jpeg images. Models for occlusion were exported in Collada format from MicroStation®.

3.1 Sliding plane

We first proposed a solution to the problem of finding the location that a drawing represents, in the presence of occlusion. Considering, for instance, the situation where a drawing represents a section of a wall that is already built. The user holds a tablet that displays a drawing where 4 sections are displayed. The user wants to know the location that one of those 4 sections represents. Upon selecting the section, the system displays it in an animation, showing it inserted into the wall, at the exact location it represents (see Figure 3). The drawing is first displayed outside of the building, then progressively inserted into it, until it reaches its correct location, and then moved out again. The drawing insertion, played a few times, is aimed at catching the user's attention, and at showing the physical location that the drawing represents. During the insertion process, the drawing is clipped by the building model, revealing only the portion of the drawing that is physically outside of the building. The drawing was displayed on a semi-transparent virtual sheet for display clarity.

Fig. 3: Example of a 2D drawing being inserted into a building.

3.2 Model clip

The sliding plane technique appears very useful for highlighting the physical location that a drawing represents, and for attracting the user's attention. However, the proposed technique has a major disadvantage: when the drawing is fully inserted in the building, positioned exactly at the location it represents, its content is occluded by the wall. To let the user see the drawing in its context, it would be interesting to apply the concept of "virtual excavation" (Schall et al., 2010) to those walls. However, the problem would then be about knowing what to display inside the excavation: the 2D drawing needs an appropriate intelligibility-providing context within a 3D environment, and an empty hole would provide no such context. As a solution, we proposed a technique based on hypermodeling: the outside wall of the building is virtually replaced with a clipped version of a 3D model revealing the inside of the building. The 3D model is further augmented by the 2D drawing, displayed within the clipped model section, in a hypermodeling fashion (see Figure 4).

In the prototype, 2 methods were used to help the user locate drawings: handles and thumbnails. Drawings thumbnails are displayed at the bottom of the view – when the user clicks on one of them, the system automatically displays the corresponding drawing in the real environment with its pre-selected model clip (resulting in a scene similar to Figure 4). Handles are small icons displayed into the scene, which the user can click on to get the same result. Those tools were implemented to provide the user with 2 ways to navigate drawings: spatially or drawing-based.

Our experiment was not limited to panoramic images. The main advantage of panoramic images is that they are a faithful representation of the physical world that can be easily understood by users. It turns out that point clouds are also faithful, and they have the additional advantage of being 3D. We hypothesized that augmenting point clouds with 2D drawings could bring the same kind of visualization and intelligibility benefits. A point cloud was therefore captured inside and outside the building, clipped, and augmented with a 2D section drawing as well as some clipped elements of the 3D model (see figure 5). Our results show that not only is the augmented representation visually clear, but it has the advantage of being viewable from any orientation, as both sets of data are fully 3D.

To get an idea of the potential of such visualization technique, our prototype was demonstrated to and/or used by about 30 CAD users. They all confirmed that potential, confirming they understood the purpose of the drawings better. Several users also pointed out that a large number of 2D drawings exist for our infrastructure, and those drawings are never used, either because they are not easy to access, or because once accessed, deciphering them requires great effort due to their decontextualized abstraction. Some also mentioned that their format (paper drawings) is not appropriate for use on site, or because they are generally out of date with the current state of the infrastructure asset. Such visualization techniques could bring those drawings back to life, enabling users to take advantage of their data, but also would offer the possibility to update and correct them more easily.

4. CONCLUSION & FUTURE WORK

In this project, we tried to address the problem of interpreting 2D engineering drawings on-site, for construction work. Drawings are abstract and numerous, and a wrong interpretation may lead to mistakes in the construction process. Our contribution consists of proposing 2 AR visualization techniques that can be used to browse a stack of drawings, searching for their corresponding location in the world, or to browse the physical world, in search of corresponding drawings.

Our results suggest that by providing a visually clear and intelligible way of displaying the drawing in the 3D scene, the techniques could potentially be useful for:

- Reducing the time required for searching for specific drawings;
- Reducing the risk of using the wrong drawing when doing the construction work.
- Reducing the risk of a drawing going unnoticed.
- Helping users more correctly, thoroughly, and easily understand the meaning of 2D drawings and their 3D spatial relationships.
- Helping users clarify the locations in a 3D model at which there exists reliable and certified graphical information.
- Generally improving the intelligibility of complex information of several types mutually when combined: drawings, virtual models, and captured reality, both photographic and point cloud.

Other studies will be required to confirm those advantages.

In construction work, drawings are essential, as they provide instructions on how to build. 3D models are also very important, as they provide a global understanding of how all the 2D drawings are aligned together to form a 3D object. Finally, the physical reality is also essential, as that is where the infrastructure is built. All 3 components, taken individually, have some value. Our results suggest that the value of aligning all 3 media together is greater than the sum of the individual values of its parts. Indeed, the alignment seems to provide the user with an improved understanding of each media, understanding that is long and difficult to obtain when using each media separately. On the design side, media alignment could also prove to be very useful, as the combined environment becomes the place within which to conceptualize, develop and deliver both the design itself, and the certified communications that serve ultimately to convey essential ideas and instructions to builders. In addition to providing a set of 2D drawings, engineers and architects could also deliver a rich, intelligible, directive, and actionable visual information environment that would enable builders to better understand the work they are doing, and will do, and therefore to better understand the whole of a project and its parts.

The proposed method is in its infancy, and could be vastly improved. The method could first be improved in terms of the quality of the rendering. Adding a semi-transparent plane behind the drawing proved to be useful for the sliding plane technique, and should also be tried for the model clipping technique, as it might improve the drawing's visual appearance. Some attention should also be put on the drawings' line thickness, to improve readability in an augmentation context at varying zoom level. A 2D view inset could also be used to display the selected drawing in 2D, when the angle of the clip does not allow easy readability.

Fig. 4: Top: non-augmented scene. Middle: scene augmented with a clipped 3D model, revealing the inside of the building, which is further augmented with a 2D drawing. Bottom: detailed view.

Fig. 5: Point cloud augmented with 2D section drawing and some clipped 3D elements.

In terms of applicability, the method has been tested on simple cases of section drawings for a building that is completely built. Other studies should be conducted in situations where:

- The building is not completed yet, or nonexistent.
- The built infrastructure was not perfectly built according to specifications, and is therefore different from the 2D drawings and 3D models.

- The drawing is a floor plan.
- The drawing represents an area that is hard to access physically, for instance a high level floor seen from the ground, or a twice-occluded area (for instance by 2 layers of walls).

Our results are only a beginning, and let us envision several other applications of AR in the construction field.

5. REFERENCES

Appel M. and Navab N. (2002). Registration of technical drawings and calibrated images for industrial augmented reality. *Journal of Machine Vision and Applications*, Vol. 13, No. 3, 111-118.

Bier E.A., Stone M.C., Pier K., Buxton W. and DeRose T.D. (1994). Toolglass and magic lenses: the see-through interface. *Proceedings of CHI '94*, 445-446.

Côté S. (2011). Augmented reality for infrastructure: a first step. Published electronically on *BE Communities*.

Dunston P.S., Wang X., Billinghurst M. and Hampson B. (2002). Mixed Reality Benefits for Design Perception. *Proceedings of ISARC*, 191-196.

Fiorentino M., Monno G. and Uva A.E. (2010). Published electronically, Tangible Interfaces for Augmented Engineering Data Management. *Augmented Reality* (Maad S., editor), InTech, 113-128.

Gimeno J., Morillo P., Casas S. Fernández M., 2011. CAD System at Construction Sites In: Augmented reality - some emerging application areas. Andrew Yeh Ching Nee Ed. Intech, Rijeka, Croatia.

Golparvar-Fard, M., Peña-Mora, F., and Savarese, S. (2011). "Integrated Sequential As-Built and As-Planned Representation with D4AR Tools in Support of Decision-Making Tasks in the AEC/FM Industry." *J. Constr. Eng. Manage.*, 137(12), 1099–1116.

Hammad A., Garrett J.H., Karimi H.A., 2002. Potential of mobile augmented reality for infrastructure field tasks. In: *Proc. of the 7th Int. Conf. on Appl. of adv. technology in transportation*, Boston, Mass., August 2002.

Kalkofen D., Mendez E. and Schmalstieg D. (2007). Interactive Focus and Context Visualization for Augmented Reality. *Proceedings of ISMAR '07*, 1-10.

Lee G.A., Kim G.J. and Billinghurst M. (2005). Immersive authoring: What You eXperience Is What You Get (WYXIWYG). *Communications of the ACM*, Vol. 48, No. 7, 76-81.

Mackay W. E., Pagani D.S., Faber L., Inwood B., Launiainen P., Brenta L. and Pouzol V. (1995). Ariel : Augmenting Paper Engineering Drawings. *Proceedings of CHI '95*, 421-422.

Mann S. and Fung J. (2001). VideoOrbits on eye tap devices for deliberately diminished reality or altering the visual perception of rigid planar patches of a real world scene. *Proceedings of ISMR '01*, 48-55.

Navab N., Bascle B., Appel M. and Cubillo E. (1999). Scene augmentation via the fusion of industrial drawings and uncalibrated images with a view to marker-less calibration. *Proceedings of IWAR '99*, 125-133.

Olsson T.D., Savisalo A.T., Hakkarainen M., Woodward, C., 2012. User evaluation of mobile augmented reality in architectural planning. In: *eWork and eBusiness in Architecture, Engineering and Construction*. Gudnason & Scherer Eds. 2012 Taylor and Francis Group.

Poirier S. (2011). *Estimation de pose omnidirectionnelle dans un contexte de réalité augmentée*, MSc Thesis, Université Laval.

Schall G., Schmalstieg D. and Junghanns S. (2010). VIDENTE – 3D Visualization of Underground Infrastructure using Handheld Augmented Reality. *GeoHydroinformatics: Integrating GIS and Water Engineering.*

Woodward, C., Hakkarainen, M., Korkalo, O., Kantonen, T., Aittala M., Rainio, K., Kähkönen, K., 2010. Mixed reality for mobile construction site visualization and communication. *Proceedings of the Construction Applications of Virtual Reality* (CONVR), Sendai, Japan, Nov. 2010.

A BIM AND AR BASED PLATFORM FOR MANAGING NON-CONFORMANCES

Pedro Berto
Faculty of Science and Technology, Nova University of Lisbon (FCT, UNL)

Nuno Cachadinha
Faculty of Science and Technology, Nova University of Lisbon (FCT, UNL), presently at Technion-Israel Inst. of Technology

ABSTRACT: *Defects and errors are common and occur repeatedly during construction projects. An effective management of non conformances is vital for a streamlined and efficient production progress. Large quantities of data and information are produced, which can be lost or misinterpreted. Several defect managing systems have been developed to facilitate measuring and correcting defects. However, few focus on data and information gathering and sharing, as well as providing an efficient communication tool for teams on site. Building Information Modeling (BIM) has proven to improve communication and information sharing. The lack of platforms that integrate BIM in the communication processes used on site is hindering the full exploitation of its potential in improving communication. The overarching aim of this research is to develop a unified real-time communication platform capable of providing richer information for the decision making in the non conformances management process. This study lays out the conceptual framework for the communication platform "C-BIM-thru-AR" (Communicating BIM through Augmented Reality). This platform integrates BIM models into the communication channels used on-site and offsite via Augmented Reality (AR) systems. To develop the "C-BIM-thru-AR", first the systems functional requirements had to be established. To accomplish this, the Integrated Definition for Function Modeling (IDEF0) technique was used to create as-is maps to analyze processes included in production management and establish functional requirements. With the functional requirements gathered and by applying a system thinking approach, the platforms framework and network architecture were developed. The proposed platform aims at enhancing the management and quality of all the information produced from the management of non conformances, ultimately improving the processes productivity. In future studies, the proposed platform could be exploited in the management of subcontractors' performance which could be stored automatically in the "C-BIM-thru-AR" platform.*

KEYWORDS: *Building Information Modeling; Augmented Reality; Unified Communication Platform; Communication; Information Sharing*

1. INTRODUCTION

The unique and fragmented nature of the Architecture, Engineering and Construction (AEC) sector is well known and documented (Isikdag and Underwood, 2010). The issues raised from this fragmentation are also well known: low productivity and poor quality (Koskela, 1992). These issues make quality control one of the major concerns, for construction professionals, besides schedule and cost overruns. Studies show that defect related rework is considered a non-value activity responsible for 12.4% of construction cost and affects the industries productivity (Josephson *et al.*, 2002). Quality systems have been implemented in construction companies to better handle the management of non-conformances. However, the increasing complexity of construction processes, the increased paperwork and administrative tasks, and the additional costs experienced by construction companies when implementing quality systems' that fulfill the ISO 9001 requisites, are limiting the adoption of this norm by the construction industry when compared with other industries (Tang *et al.*, 2005). In addition, construction staff's natural reluctance towards paperwork and administrative tasks has decreased the acceptance of ISO 9001 compliant quality management systems.

Citation: Berto, P. & Cachadinha, N. (2013 A BIM and AR based platform for managing non conformances. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Some systems have been developed to handle defects occurred during construction (Park, 2012; Kim, 2008; Yu, 2007; Wang, 2008). However, the growing complexity of production management processes and the extensive array of specialists involved and their growing geographic dispersion, make information gathering and sharing a great effort managing the information produced between onsite and offsite personnel is yet to be addressed.

Building Information Modeling (BIM) has proven its benefits as a tool capable of enhancing communication and collaboration in construction (Sacks *et al*., 2010). In contrast to the primary and traditional communication channels used on site, based on two dimensional (2D) drawings and other paper based documents, BIM can support and provide process visualization of construction projects (Chelson, 2010). Moreover, BIM offers extended visualization features capable of reducing project process related problems, including quality defects (McGraw-Hill, 2008). However, issues on how BIM can surpass design to real-time on site construction still persist (Wang and Love, 2012), forcing BIM to be mainly used as a representation and simulation tool (McGraw-Hill, 2008).

In order to fill these gaps, this study proposes the integration of BIM models in the communication channels used on site through the use of augmented reality (AR) systems. To achieve this, a conceptual communication platform, has been developed to allow onsite and offsite construction teams to communicate and exchange information effectively. This relies on BIM and AR, where BIM models provide a tool to enhance the performance of informational tasks executed on site, and AR systems support the gathering and storage of information from the construction site into a single BIM model. The aim is to provide an effective tool, capable of monitoring quality control and enabling an effective interaction and real time data sharing, independent of user's geographical location.

2. LITERATURE REVIEW

2.1 Traditional Management of non conformances

The construction industry is characterized as information-intensive, where creating and sharing information is a cumbersome process. Despite all the research undertaken in identifying better methods for information sharing, it is still a time consuming activity. Generally, time is wasted on locating appropriate information or providing redundant information. This can be explained by the industries reluctance in changing the primary and traditional communication channels, based on 2D drawings and paper based documents and graphics, despite many researchers claiming that these channels are insufficient to guarantee a suitable communication, thus hindering productivity (Chelson, 2010; Sacks *et al*., 2010).

Similarly to other construction processes, managing non conformances also relies on traditional communication channels to record and share information. Traditionally, defected works are detected and recorded on 2D drawings or other paper based documents. The gathered data is then delivered to the site office, where it is rearranged and transposed into standard documents or into a computer system. This transition can result in data loss or misinterpretation. In addition, the data is often gathered, recorded and transformed into information by different individuals, with different roles and backgrounds. This harbors significant potential for misinterpretations (Golparvar-Fard, 2009). Moreover, data is often omitted or miswritten when converted (Park, 2012). Finally, work orders are issued based on this information and the necessary work is carried out. Often enough, this information needs to be transmitted to other stakeholders down the production line, such as subcontractors and suppliers. This is yet another step where the quality of the information transmitted can be worsened. This can result in ineffective rework which fails to eliminate the non-conformance detected.

Quality management plays an essential role in the construction industry (Wang, 2008). Despite modern quality practices not being able to guarantee a flawless product or service, their implementation in non-conformance management processes brings several benefits to the construction industry (INGAA, 2013). The same report states that these benefits include: Process improvement and a factual approach to decision making; Enhanced stakeholder satisfaction; increased efficiency; better planning; Continuous improvement; Improved Employee Morale; Improved control over documentation (INGAA, 2013). Besides the benefits that quality systems bring, they are responsible for assuring that the ISO 9001 requisites are fulfilled. In fact, implementing a system for managing non conformances is one of the major requisites prescribed by the norm. Thus, this is a particularly relevant issue for companies that aim at obtaining and maintaining ISO9001 certification.

Several systems have been developed to manage non conformances. Park (2012) classifies them depending on their approach as reactive or proactive. Systems including RFID technology (Wang, 2008), personal data assistants

– PDA's (Kim *et al*., 2008) and laser scanners (Yu, 2007) work reactively after non conformances occur. On the other hand, systems including some form of augmented reality system (Park, 2012) work proactively in managing non conformances before they occur, by continuous monitoring and early stage detection.

2.2 BIM – A tool for onsite communication

In contrast with the traditional 2D and paper based communication channels, BIM supports and provides the visualization of the project and construction processes. The development of 3D visualization through precise BIM models enhances the visualization potential of the physical and functional means of a facility, representing a great advantage for the stakeholders (Chelson, 2010). Thus, BIM can provide the necessary means to alter the communication dynamics encountered on site. BIM can aid construction professionals by simulating the future environment of a building, thus allowing the identification of possible project or production errors (McGraw-Hill, 2008). According to Sacks *et al.* (2010), communicating the project intentions effectively is one of the key functionalities of BIM, along with providing the opportunity to transmit information in dynamic views. These benefits can directly improve communication, making production meetings more effective and efficient (Sacks *et al.*, 2010). In addition, they pave the way for information sharing tools and for the enhancement of the communicational channels between production managers and onsite teams.

2.3 AR – Bridging the Visualization Gap

Froese (2010) describes the three technological eras witnessed in construction. Wang and Love (2012) mention a fourth era, where digital project information (BIM models), generated prior to construction, is brought to the construction sites. AR is the technology envisaged to bridge the visualization gap between office and onsite environments, through the visualization of digital information in the physical context of each construction activity or task. Further in their research, Wang and Love (2012) sustain that the visualization of BIM models on the construction site can improve the industry standards in the following key areas: interdependency; linking digital (paper) to physical; synchronization of mental models for communication; project control, monitoring and feedback (as built vs. as planned); material flow tracking and management in procurement; bridging the visualization gap from design to production; site plan and storage of materials.

Recent studies have identified AR application areas in Construction. Production management is one of the areas that can potentially benefit from AR systems. In particular, the informational tasks performed onsite have been investigated and the visualization opportunities existing in the use of this technology discussed (Shin and Dunston, 2008). The same study demonstrates how activities performed on site can largely benefit from the visualization of virtual models through AR applications. Activities related to planning and supervising both include intense information tasks like coordination, strategy, supervision and commenting, where all of them can benefit from the potentials of AR systems: digital information tagging and reliable 3D virtual models superimposed onto the real scene.

3. RESEARCH METHOD

The strategy used was based on a systems approach (Ramo and Clair, 1998), where construction processes adopted onsite are considered as part of a system - Production Management. The objectives consisted of modeling the entire operation included in the non conformances management process and then define the functional requirements for the "C-BIM-thru-AR" platform. In order to achieve this, the research was divided into two phases:

Phase 1: Process Analysis – Case Study

A case study was performed in order to model all operations behind the "non conformances management" process included in the production management process of a Portuguese Construction SME whose production is centered in building. The functional requirements for a conceptual communication platform were captured using the IDEF0 modeling technique. *As-is* maps were created towards analyzing processes and establish functional requirements.

Phase 2: Process Modeling – "C-BIM-thru-AR" framework development

Based on the findings and insights obtained through the literature review and the functional requirements captured in phase 1, the "C-BIM-thru-AR" systems framework and network architecture were developed by adopting a systems thinking approach, where the informational tasks that compose the management of non conformances process are integrated into BIM models. Enhanced visualization is then achieved by adding the information generated during this process to the virtual models utilized, which are superimposed to the actual physical context though an AR system.

4. PROCESS ANALYSIS – CASE STUDY

Using the IDEF0 modeling technique, all the activities and relations between them, included in a specific process of production management, "Managing non conformances" were modeled. The chosen process for the current study is one of the most important processes included in production management of any type of construction project.

4.1 Modeling the Production Process

The chosen process for modeling involves all activities included in the following sub processes: controlling and supervising production; resolving non conformances; hand over building. The process was decomposed into higher levels of details (A0, A1, …, A21, …, A311, …, A422), in order to capture all the interconnected relations among the various processes.

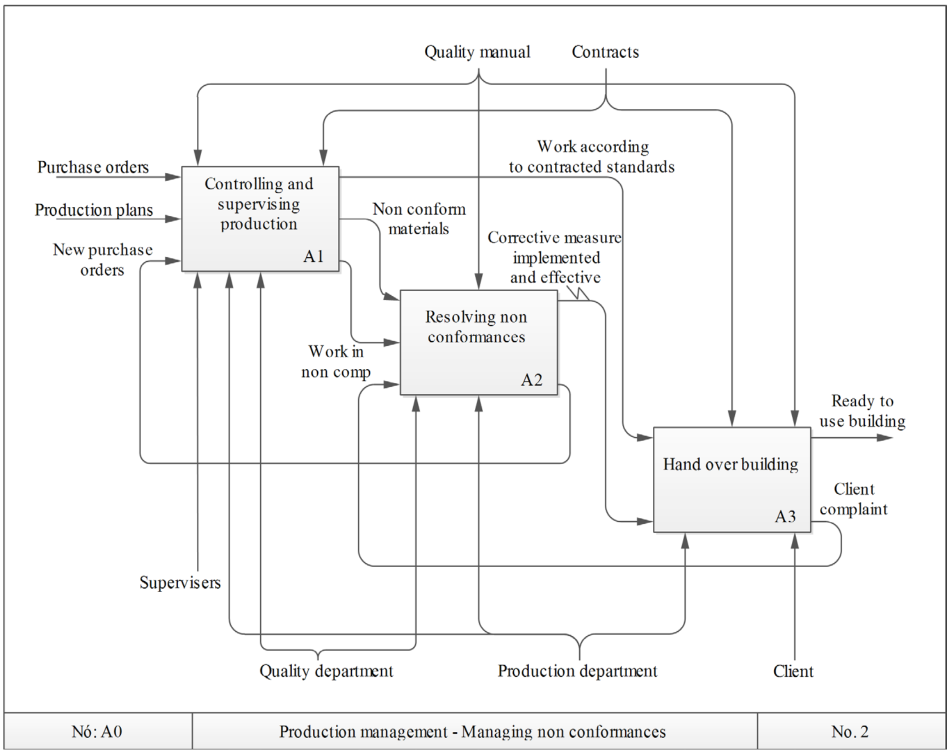


Fig. 1: Production management process – managing non conformances

4.2 Decomposing the production process

The main sub-processes and activities that form the "Production management process – managing non conformances" are shown in Fig. 1. As shown in the diagram, there are three main activities in the mentioned process, with information exchange and interactions between them also being identified. In order to reach the interactions between teams and workers onsite and capture information exchange between them, it was necessary to decompose each of the represented activities in two levels of detail. The analysis was then centered in ascertaining the main needs of each activity concerning documents, protocols, tools and constrains. It was also possible to acquire knowledge about the strong and weak points of the procedures of each activity.

4.3 Establishing Functional Requirements

At the end of the process analysis and by the conclusions taken from the different interviews, the functional requirements for a communication application for production management were identified. Comparing the identified requirements and the current process deficiencies, it was possible to develop a framework for the C-BIM-thru-AR application. These requirements were first grouped into two sections that represent the main primary needs of the production management process: sharing data, represented in Fig. 2 and gathering data, represented in Fig. 3. With the IDEF0 *as-is* maps the authors were able to identify the deficiencies of the actual process and, by crossing them with the needs gathered from the different staff and stakeholders interviews, the functional requirements for a communication application for the managing non conformances process were clearly identified.

In each section, functional requirements were identified that could fulfill the needs of the studied process. In order to respond to sharing data needs, the proposed application has to provide easy access and correct standardized

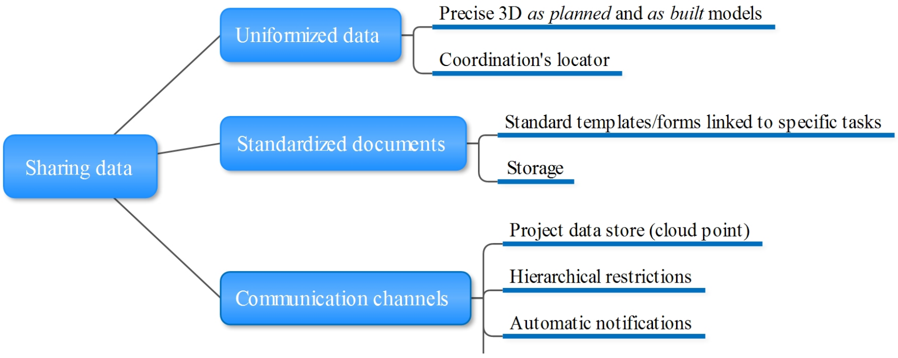


Fig. 2: C-BIM-thru-AR functional requirements – Sharing data requirements

documents, uniformed data which is not subject to misinterpretations, , and effective communication channels.

Fig. 2 illustrates the application's tools associated to each functional requirement: precise 3D models, coordination's locator, standard templates/forms, storage, sharing information cloud point, automatic notifications and open class formats. The functional requirements for the gathering data section were divided into two distinct sub-sections: Onsite data capturing and office data capture. Both locations share the same needs related to gathering data. However, due to their physical nature differences, each of them has specific functional requirements, as illustrated in Fig. 3.

5. COMMUNICATING BIM THROUGH AUGMENTED REALITY, C-BIM THRU AR

A system framework (Fig. 4) and its associated network architecture (Fig. 5) have been developed in order to create a bidirectional flow of information between construction job sites and different stakeholder's workspaces. In this context, the C-BIM-thru-AR conceptual platform focuses on the visualization and modification of project data and information sharing during a specific production management process – Non conformances management. Design and calculations processes were not considered at this stage. Therefore, this concept is intended for management purposes throughout the construction phase of any given project. It is suited for all stakeholders involved in the production management process, i.e. superintendents, site managers, project managers, production and quality managers. The C-BIM-thru-AR platform consists of two interdependent modules: one for construction site use (C-BIM supervisor), another for office use (C-BIM manager). These modules are available to the users as intelligent interfaces which are differentiated by their functionalities, display devices, tracking devices, AR systems for virtual models visualization and permissions to access project information by limiting the number of databases connected to each tool. Their functionalities will be described in the next section.

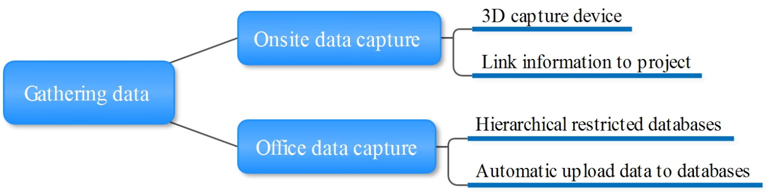


Fig. 3: C-BIM-thru-AR functional requirements – Gathering data requirements

The C-BIM supervisor main functionalities are supervising and commenting. The display devices proposed include a tablet pc for image displaying and a specialized digital camera for 3D reconstructing. This module

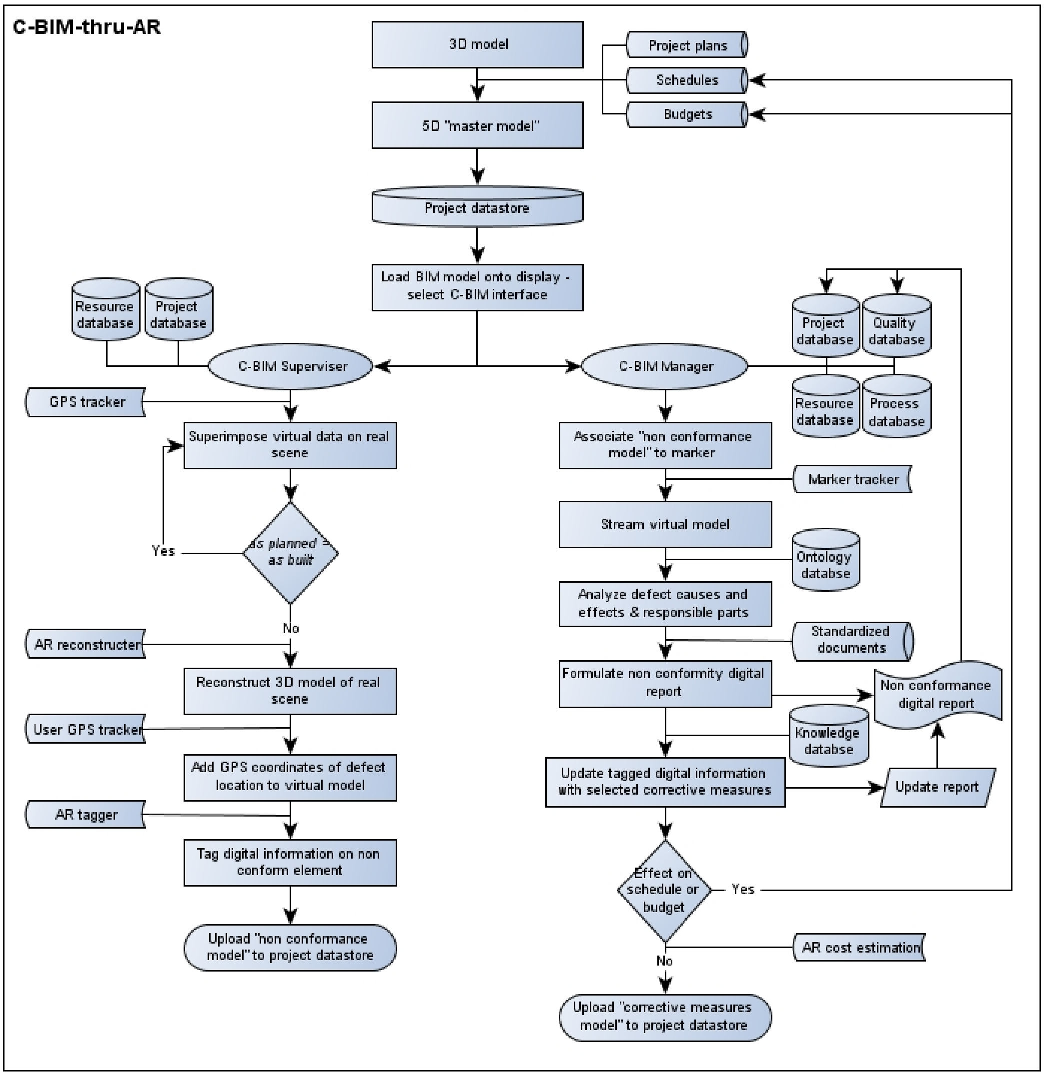


Fig. 4: Conceptual system framework for enhanced onsite communication

feature works similarly to the prototype developed by TNO, Netherlands Organization for Applied Scientific Research, for 3D model reconstructing with the objective of securing crime scenes (TNO, 2012). The module uses a sensor based tracking system (GPS), incorporated in the tablet pc to track the user's position and an attached electronic compass, to track the user's orientation. An AR system provides augmented reality visualization, interaction with the user and information capturing, where the viewing projection is provided by the C-BIM-manager server. The necessary technological solution already exists. It was developed by VTT, Technical Research Center of Finland and applied to its OnSitePlayer module, i.e., the software application AR4BC (Woodward *et al*. 2010). In terms of linked databases, it is limited to project and resource databases.

The C-BIM manager's main feature is the possibility of managing and modifying project information and documentation based on the information gathered on the construction site, and instantly updating new information through its standardized document database. Each available document type is linked to a specific task, i.e., as soon as the site manager wants to report a non conformance, the system automatically opens a non conformance standard document. Its display devices are either portable pcs or desktop pcs with powerful graphic processors, equipped with a digital camera. It uses an optical based tracker (markers) to track the virtual models and has live stream functionality. The visual projection of the virtual models is also done by an AR system. In this module the viewing projection system will be similar to ArToolKit, by the Human Interface Technology Laboratory (HitLab) and ARToolworks, Inc (Kato, 2003). In addition, by connecting the AR system to specific databases, it provides the user with an automatic cost generator option, used when adding new construction elements to the project model. This functionality basically works in a similar way to the construction management simulation utilized in Real Person Games. A list of construction materials from the company's resource database is made available to the user through the C-BIM manager interface, together with a picture of the resource and the associated costs. The user then chooses the desired material and its quantity, and cost estimation is automatically added to any report or model updates. Concerning physical workspace, the C-BIM manager designed to be used in distinct geographical and functional areas, such as onsite and offsite offices, with differentiated access to the databases available, according to the role of the user.

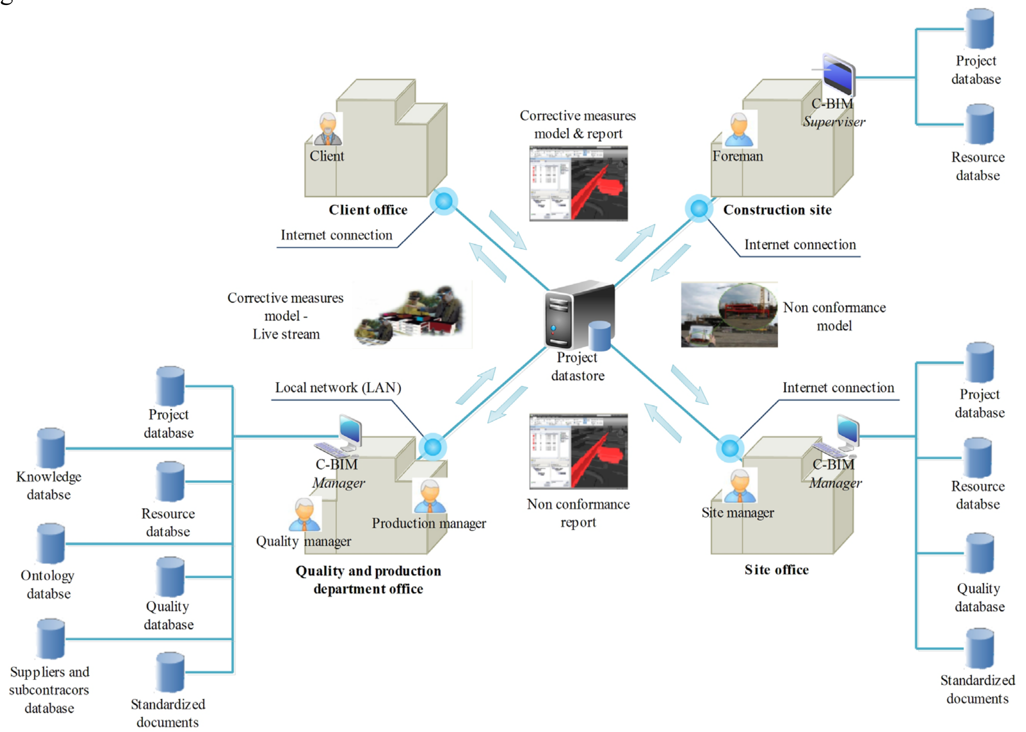


Fig. 5: Conceptual network architecture for online information sharing

5.1 System's conceptual framework

Following the functional requirements established in the previous chapter, an efficient tool to enhance and improve information sharing and real time communication in managing non conformances should focus on shared data immune to misinterpretations and an informational and communicational tool, both for onsite and offsite use, capable of gathering data in real time. Fig. 4 shows the system's main functionalities and processes. The system uses roll based interfaces in order to facilitate its use and mainly to create a hierarchical access to the project information. As mentioned, two different interfaces have been conceptually developed. The interfaces were developed having in mind the possible optimization of the non conformances managing process and the user's role, workspace and professional needs.

"C-BIM supervisor" is exclusively for onsite use. By logging into the system through the supervising role, the interface superimposes 3D models (imported from the project data store) on to the real scene by an augmented reality system, combined with GPS tracker. This permits the user to compare *as planned* data with *as built* data. When the user detects any kind of defect, he freezes the image and initiates a 3D reconstruction of the defected element. With the commenting functionality, the user can accurately tag the defect coordinates on to the BIM model and add digital information about the defected element.

"C-BIM manager" is aimed for office use. By logging into the system through the onsite managing role and downloading the "non conformance model", the user can now access different databases. By associating the downloaded model to a marker, the user can project upon any surface in his or her present location, in order to have better perception of the defected element though spatial, interactive visualization. With the linked ontology and standard document databases, the user can accurately fill out a non conformance report. In the office managing role, the user has access to all the project related databases, live stream and cost automatic adjustment. Reports can be updated and visual information can be shared with the client and with the AR budget functionality, which is linked to the resource database. He or she can then add constructive elements to the "corrective measures model" and estimate the respective rework cost. The database should include simple and composed costs.

5.2 System's network architecture

Fig. 5 shows the interconnections between different stakeholder's workspaces and the cycle for the non conformance management process. The first stage of the proposed system focuses on project monitoring and supervising from the construction site perspective and tracking of the building elements production and quality. In the previous chapter the role of the "C-BIM supervisor" was described for this use. In the process of tracking the occurrence of non conformances and proceeding to their rework, various parties are involved. The onsite crew tracks and updates the status of the building elements. The information is transmitted from the "C-BIM supervisor" interface to the project data store and from there to the on-site office via "C-BIM manager". At this point the "non conformance model" consists of a virtual model tagged with digital information, with the non conformance location coordinates and with its 3D reconstructed model. The model is made available to the site manager, who uses it for detailed planning and for submitting accomplished work reports. The site managers analyses the need for rework. Using the *as planned* 3D models they become aware of impacts on the current planning schedule. A non conformance report is then formulated with "C-BIM-manager" standardized document database.

As soon as the site manager submits any type of report, production and quality managers are notified. The system's hierarchical restrictions allow these departments to access further databases, besides the interface layout and access privileges of the site managers. These restrictions are intended to keep the system light, functional and to reduce the complexity of the production management processes. From the user's point of view, the system's role restrictions limit access to the strictly necessary documents and databases for users to perform their activity in an effective way. By accessing all available databases, the production and quality managers are able to evaluate the causes of a non conformance and chose the most appropriate corrective measures, with the help of a knowledge data base that includes previous experiences in other projects. At this point the "corrective measures model" consists of a virtual model tagged with digital information, which includes the non conformance location coordinates, its 3D reconstructed model, the rework instructions and the cost estimation of the rework.

The cycle is ended by communicating the adopted corrective measures to the client and back do the construction site. The communication and information sharing, between off-site office and client, is guaranteed by the marker based AR viewing projection and live stream functionalities. The offsite office user projects the virtual model in the office, with its respective 3D reconstructed models, and interacts with the client through the live stream option. With this communication channel, the client can visualize the models and simultaneously observe the offsite office user's gestures and instructions. This provides the client with the opportunity to actively participate in the assurance of the project's quality standards, despite of his or hers current location. From the perspective of the onsite users, they are notified as soon as the "corrective measures model" is approved. From then on they can access rework instructions, annotated drawings and reports of the non conform element, all available in the project data store. Through a simple color code applied to the several reports the site manager is provided with a prioritized work list.

6. DISCUSSION

A significant number of software applications and different formats are used in *C-BIM-thru-AR* throughout the entire project. This anticipates interoperability issues, which will have to be dealt with before the proposed framework can be implemented. Interconnecting all different documents formats and databases and the proposed systems will be particularly challenging. An anticipated strategy for addressing these issues is the utilization of Industry Foundation Classes (IFC) formats by all software applications when processing their respective data and documents, thus allowing for a smooth incorporation into the proposed system interfaces. Another obstacle to overcome is the potential intellectual property issues arising from the fact that a number of different proprietary AR systems are considered in the framework of the proposed platform. It utilizes functionalities from four different AR applications: 3D reconstruct; digital information tag; visualization of virtual models, and automatic generation of costs. At the same time, the tracking technology considered (GPS) doesn't provide pin point accuracy and has issues in sub terrain structures. Hammad (2004) reviews several existing tracking technologies and their associated accuracies. This author states that hybrid systems can achieve desirable accuracies when using multiple measurements obtained from different sensors to compensate the shortcomings of each technology when used individually. A promising hybrid system for solving tracking issues consists of measuring position by differential GPS, and inertial tracking and orientation by a digital compass and tilt sensors. The integration of the measurements from different positioning techniques from the different sources involved can be obtained through the use of a *Kalman* filter, which also performs data homogenization and noise reduction. (Hammad *et al*., 2004; You and Neumann, 2001).In terms of potential benefits for production management, the proposed application can easily be adopted by construction companies due to its simple and user friendly interfaces. The users will need minimal training to rapidly master all the application's functionalities. The application was modeled considering functional requirements and the professional needs identified throughout the interviews performed for the case study. As a result, C-BIM-thru-AR provides better means for decision making, with its real time communication and information sharing capabilities – based on AR systems – thus increasing the stakeholders' awareness by continuously updating the jobsite's progress. In addition, stakeholders' satisfaction is enhanced since all information is kept in the project data store module, each user has permanent access to project information (original project and all its updates) according to role privileges, and virtual visits to the construction site are enabled to the stakeholders from any location. This feature is particularly interesting due to Construction's growing globalization. Besides, a continuous improvement of the construction companies' projects is also enabled, since past construction issues and defects are stored and easily accessed. Thus, it is possible to avoid recurrence of issues and defects. By providing a software tool for onsite use based on the projection of BIM models by AR systems linked to all relevant databases, a better documentation control and management is achieved, allowing the users to access any type of document in real time, regardless of their location.

The costs of implementing new ICT tools can also be seen as an obstacle, especially if a recent investment has been made by the stakeholders in other ICT tools. Comprehensive cost-benefit analyses will need to be carried out, taking into consideration the expected ROI of the previous investments and the expected benefit from the implementation of this system. This is particularly challenging, as it is difficult to quantify the benefits of enhanced communication and improvement in human, professional relationships onsite and the benefits that they bring about. Cost-benefit analyses of new ways of performing work are always challenging, as something known needs to be compared with something that will be. This is particularly felt in software projects. Another fundamental aspect that needs to be guaranteed is the adherence of the client to this platform and *modus operandi*. The fact that C-BIM-thru-AR does not require the client to acquire specific technology, other than conventional live stream applications, greatly facilitates this step, as the benefits brought about by this platform will be made available to the client without extra costs.

7. CONCLUSIONS

This paper first modeled the operations associated to the process of detection and resolution of non conformances, followed by the building production department of a Portuguese SME. Then, the "C-BIM-thru-AR" framework, its conceptual communication platform and network architecture were proposed. This study focused on the objective of transmitting accurate and consistent information from the construction site to different workspaces, thus increasing the production management means to face the unexpected issues that always arise during construction projects. Information exchange with third project participants, such as subcontractors and suppliers, is not yet considered. Future works should include imbedding subcontractors' and suppliers' performance assessments in the proposed system's database. This will enable a real time automatic update of the databases with information gathered in the work front and processed in the site office. Ultimately, concentrating all information exchange and communication channels used by all stakeholders and project participants into the C-BIM-thru-AR platform is sought, with the incorporation into the platform of an automatic workflow notification tool. This can be achieved by the development of new interfaces for every role included in construction projects.

8. REFERENCES

Chelson D. (2010). Published electronically, The effects of building information modeling on construction site, University of Maryland. <Available at http://drum.lib.umd.edu/bitstream/1903/10787/1/Chelson_umd_0117E_11427.pdf > *[Accessed March 24, 2013]*

Froese T. (2010). The impact of emerging information technology on project management for construction, *Journal of automation in construction*, Vol. 19, No. 5, 531-538.

Hammad A., Garrett J. H. and Karimi H. A. (2004). Location-Based Computing for Infrastructure Field Tasks, In Telegeoinformatics: Location-Based Computing and Services, 287-314.

Isikdag U. and Underwood J. (2010). Two design patterns for facilitating Building Information Model-based synchronous collaboration, *Journal of automation in construction*, Vol. 19, No. 5, 544-553.

Josephson P. E., Larsson B. and Li H. (2002). Illustrative benchmarking rework and rework costs in Swedish construction industry, Journal of management in engineering, Vol. 18 (2), 76-83.

Kato H. (2003). Inside ARToolKit. <*Available at:* http://www.hitl.washington.edu/artoolkit/Papers/ART02-Tutorial.pdf > *[Accessed March 24, 2013]*

Kim Y. S., Oh S. W., Cho Y. K. and Seo J. W. (2008). A PDA and wireless web-integrated system for quality inspection and defect management of apartment housing projects, *Journal of automation in construction*, Vol. 17 (2), 163-179.

Koskela L. (1992). Application of the new production philosophy to construction, *Technical report*, Stanford University.

Leung S., Mak S. and Lee B., (2008). Using a real-time integrated communication system to monitor the progress and quality of construction works*, Journal of automation in construction*, Vol. 17, No. 6, 749-757.

Love P., MacSporran C. and Tucker S. (1996). The application of information technology by Australian contractors: toward process re-engineering, *4th Annual Conference of the International Group for Lean Construction, Birmingham, UK.*

McGraw-Hill Construction (2008). Building Information Modeling trends smart market report, New York.

Ramo S. and Clair R. (1998). *The Systems Approach: Fresh Solutions to Complex Problems through Combining Science and Practical Common Sense*. KNI, Anaheim, CA

Sacks S., Radosavljevic M. and Barak R. (2010). Requirements for building information modeling based lean production management systems for construction, *Journal of automation in construction*, Vol. 19, No. 5, 641-655.

Shin H. and Dunston P., (2008). Identification of application areas for augmented reality in industrial construction based on technology suitability, *Journal of automation in construction*, Vol. 17, No. 7, 882–894.

Tang S., Ahmed S., Aoieing R. and Poon S. (2005). Construction quality management, Condor Production Co. Ltd, Hong Kong, China.

The INGAA Foundation, Inc. (2013). Practical Implementation of a Construction Quality Management System (CQMS).

TNO (2012). 3D CSI tool. <*Available at: http://www.tno.nl/downloads/3D_reconstruction.pdf*> *[Accessed March 24, 2013]*

Wang L. C. (2008). Enhancing construction quality inspection and management using RFID technology, *Journal of automation in construction*, Vol. 17 (4), 467-479.

Wang X. and Love P. (2012). *Proceedings of the 2012 IEEE 16th international conference on computer supported cooperative work in design*, BIM + AR: onsite information sharing and communication via advanced visualization.

Woodward C., Hakkarainen M., Korkalo O., Kantonen T., Aittala M., Rainio K. and Kähkönen K. (2010). *10th International Conference on Construction Applications of Virtual Reality,* Mixed reality for mobile construction site visualization and communication.

Yang J., Ahuja V. and Shankar R. (2007). *World building congress (CIB)*, Managing building projects through enhanced *communication* – an ict based strategy for small and medium enterprises.

You S. and Neumann U. (2001)., Fusion of Vision and Gyro Tracking for Robust Augmented Reality Registration. Proceedings of the Virtual Reality 2001 Conference

Yu S. N., Jang J. H. and Han C. S. (2007). Auto inspection system using a mobile robot for detecting concrete cracks in a tunnel, *Journal of automation in construction*, Vol. 16 (3), 255-261.

PART IV: BIM & VR IN EDUCATION, LEARNING AND COLLABORATION

ecoCampus: A NEW APPROACH TO SUSTAINABLE DESIGN EDUCATION

Steven Ayer, John Messner & Chimay Anumba
The Pennsylvania State University, United States of America

ABSTRACT: *Civil and architectural engineering education programs strive to prepare students to design built environments that will be used by society. Some of these built systems can be challenging for laypeople to visualize while learning the design process. This research focuses on improving the way that students visualize and engage with building design content through the creation of a novel educational tool for designing sustainable building elements. The tool prototype, called ecoCampus, is an educational game that uses augmented reality technology on a mobile computing platform. It allows users to visualize a possible building retrofit design in the context of an existing built space and also receive tailored feedback about their design. The prototype application was tested with 47 first-year architectural engineering students to better understand the benefit of this tool. The results of this implementation were analyzed and compared to the results of prior semesters' students who were tasked with completing a similar retrofit design activity without the use of ecoCampus or a mobile computing device. This comparison suggests that students who completed the ecoCampus activity were more likely to complete multiple design iterations as well as experiment with materials other than those present in the existing wall, suggesting that ecoCampus may help to break the tendency toward design fixation. Additionally, students generally rated the experience as highly enjoyable, suggesting engagement with this teaching tool. Future work will implement the ecoCampus experience with students in several building-related majors to identify possible additional benefits that can be observed.*

KEYWORDS: *ecoCampus, Simulation Game, Augmented Reality, Engineering Education, Situated Learning Theory*

1. INTRODUCTION

Educators strive to prepare students to solve challenging design problems with creativity and sound reasoning. In the context of the built environment, the engineering process requires an ability of an engineer to visualize a possible building design as well as to assess the implications of the given design to understand how the building will perform and also how it will interface with its physical surroundings. This ability to visualize building geometry and analyze a design's performance can be challenging for new engineering students to perform (Dede et al. 1999). It requires a background in the fundamental engineering principles necessary for accurate assessment of performance as well as a developed ability to envision how a particular building design might look in a given setting. Despite the potential challenges associated with completing engineering design processes for new engineering students, the expectations for what the future cohort of engineers is expected to comprehend continues to grow (National Academy of Engineering 2004). This research aims to leverage emerging computing technologies to reduce or eliminate some of the visualization and analytical understanding barriers that can inhibit newer engineering students' abilities to effectively solve design challenges. This can allow students to take a learn-through-doing approach, which has been suggested to offer educational benefit in gaining knowledge that will eventually be applied to a given task as in building design (Lave & Wenger 1991). This may also offer the potential for students to gain an understanding of concepts that they might not otherwise learn until later in their academic careers because of the challenges with presenting this content early in the academic process.

Visualization plays a critical role in the engineering problem solving process, but it is not frequently stressed in education (Finke 1990; Finke et al. 1996). New technologies may be able to offer some help to students to allow them to more easily visualize building designs. This work specifically examines the benefits of augmented reality (AR) for helping students to visualize building designs in the context of an existing physical space. In addition to helping students visualize building design content, a basic simulation game has also been incorporated into the experience to provide instantaneous feedback to students to help them analyze design ideas.

Citation: Ayer, S., Messner, J. & Anumba, C. (2013). ecoCampus: a new approach to sustainable design education. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Mixed reality involves the merging of the physical and virtual worlds (Milgram & Kishino 1994). As a subset of mixed reality, augmented reality allows a user to experience a predominantly real view of a physical space with certain virtual information overlaid on top of his or her view of the space. In the building context, AR technology can allow a designer to view full scale virtual representations of building design content in the context of an existing space or project site. This may help to reduce some of the challenges and errors that can be present when new engineering students attempt to create mental models to envision complex building geometry.

In addition to the potential for AR to improve visualization, simulation games may be able to offer benefit in helping with design analysis. Simulations are models that attempt to approximate a situation, environment, or set of events to predict, teach, or entertain (Prensky 2004). Games, on the other hand, are defined as: having rules; having variable and quantifiable outcomes; having value assigned to possible outcomes; requiring player effort; requiring a player to become attached to the outcome; and having negotiable consequences (Juul 2003). Simulation games are, therefore, defined as contests where users move toward specific goals under sets of conditions and constraints that will sufficiently model a real world situation (Gredler 1994; Jacobs & Dempsey 1993). Properly used simulation games may be able to help engage students with course content and let students experiment with different design options, while providing feedback to help students analyze the pros and cons of each design idea.

This research examines the potential of using these technologies in tandem to improve certain aspects of the design process for new engineering students. To understand the benefits and challenges of these technologies, an educational game called ecoCampus was developed. ecoCampus uses AR technology in a simulation game to test students' abilities to redesign a building element in an existing building to attempt to make it perform even more sustainably. The topic of sustainability was targeted as a core design goal for this activity because of the prevalence of sustainability in the building industry (Bernstein 2010) as well as the wide variety of building design challenges that relate, in some way, to a building's overall sustainable performance. Eventually, ecoCampus is envisioned to offer several different design modules that will test students' abilities to design a variety of different building elements for existing areas on a given campus, which will broaden the possible impact of the ecoCampus design experience. By focusing on sustainability for all design modules, students will not only be able to design a variety of individual building systems, but also see how the decisions made for one system may affect others with regard to sustainability. For this initial prototype, one focused design module has been created. The findings from this first implementation will help to shape the development of future design modules.

2. METHODOLOGY

This research presents an application, called ecoCampus, which has been developed to enhance sustainable building design education through the use of augmented reality in conjunction with a simulation game. ecoCampus was designed to help students: Brainstorm different "what if" design scenarios to determine what they believe to be the best possible design solution to the given design challenge; Visualize virtual full-scale prototypes of their design ideas through augmented reality; Receive tailored feedback through a basic simulation game to shape subsequent design iteration thought processes; And, ultimately, learn sustainable design concepts through these actions.

First-year engineering students were tasked with redesigning a particular building component in an existing facility to attempt to make it perform more sustainably. While students were primarily challenged to create a sustainable design, they were also challenged to consider other design concerns such as aesthetics, cost, and constructability. For this work, students were asked to redesign a component on an existing building on campus. Because of the variety of impacts that an exterior wall design can have on sustainable building performance, students were tasked with redesigning the exterior wall on the LEED rated Stuckeman Family Building on campus. Prior to the design activity, the first-year engineering students had been presented with a basic overview of the LEED rating system in class as well as an out of class tour of the Stuckeman Building that discussed applied sustainable design and construction strategies. During the ecoCampus design activity, students would not only be required to tap into their existing knowledge of sustainable concepts from class and the building tour, but also to gather pertinent information from the simulation feedback provided in ecoCampus.

To assess the outcomes of the ecoCampus design activity, students were given pre- and post-tests before and after completing the activity to identify areas where their thought processes or understanding of sustainability may have been influenced by the format of this design activity. These pre- and post-activity assessments were designed to elicit feedback about students' understanding of sustainability and their impression of the design activity, as well as basic demographic information about the students. The assessments included multiple choice and Likert-scale questions as well as open ended questions for students to complete, which helped to generate qualitative and quantitative data for evaluation. As a point of comparison, this design activity had been completed by first-year engineering students in prior semesters using more traditional, paper-based, methods of design instead of the computerized ecoCampus format. These prior implementations had been completed by 65 students with only blank sheets of paper with no suggestions on how to perform a sustainable redesign (Ayer et al. 2013b) and another 23 students with printed images of the existing space on which to illustrate design ideas with suggestions of possible building materials to consider in their designs (Ayer et al. 2013b). In both of these prior efforts, the design goal of creating a new exterior wall, the time involved to complete the task, and the self-directed nature of the activity remained constant. Only the format of the activity was changed. These prior works help to isolate the variable of the augmented reality and simulation game technologies on a mobile computing platform from the act of completing a specific building redesign problem. Other than the differences in the format of the activities, all students who completed any design activity completed the same class activities. Fig. 1 shows the process that the students followed. The only change between the different formats would be what form of the activity was completed where “ecoCampus design activity” is currently listed. After the students completed the activities associated with this work, the responses to the pre- and post-test assessments, in addition to the data that was collected during the design activity, were analyzed to determine the aspects that may have been affected by the ecoCampus design experience.

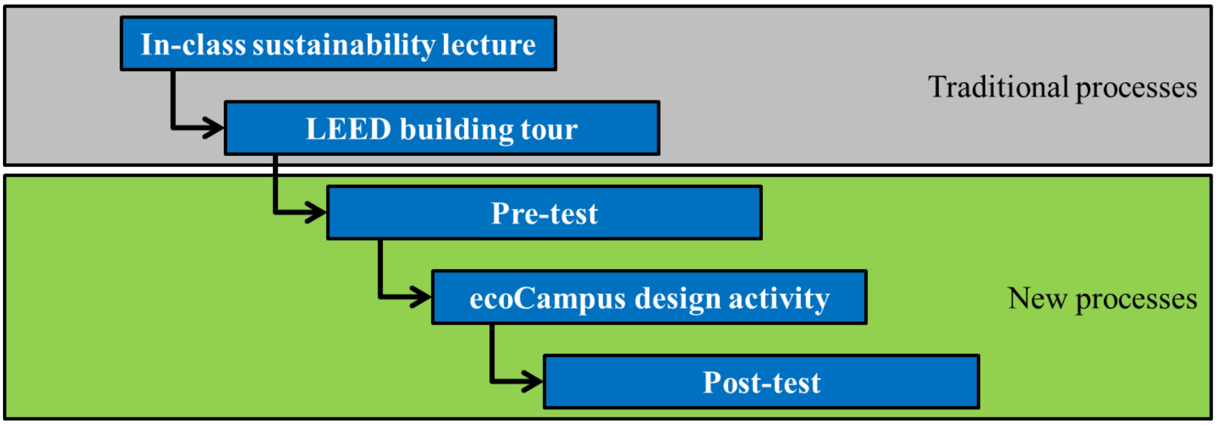


Fig. 1: Students completed several activities related to sustainability during research.

2.1 Design Activity

Students were given a 50-minute class session to complete the sustainable design activity. Students were physically present in the Stuckeman Family Building space shown in Fig. 2. This building has a predominant

Fig. 2: The Stuckeman Family Building’s curtain wall can be seen with the rectangular "ae" fiducial marker.

exterior curtain wall with typical bays on the 4th floor of the building for most of the architecture students' studio space. Students were asked to redesign the typical curtain wall bay where the rectangular "ae" sign visible. This printed sign served as a fiducial marker for ecoCampus to allow students to view their design at full scale in the context of the existing space. At the beginning of the design session, students were given a brief, five minute overview of the ecoCampus workflow so they would understand how to use the application. After this overview, students were each given a mobile computing device on which to work for the class session. Students were given approximately 40 minutes to complete the design activity with ecoCampus. They were told that they must complete a minimum of one design idea, but were free to create more as time would permit. As they would complete different designs using ecoCampus, they would take screen captures on the provided iPad so that they could later reexamine their work to recall what they had done in a given design iteration and what they had learned. In the last five to ten minutes of class, students were asked to stop their design work and reflect on their ecoCampus designs. They were asked to review each design iteration along with the feedback generated and indicate whether or not they agreed with the provided feedback.

2.2 ecoCampus Workflow

The ecoCampus experience consists of three steps that students followed during design. Users would first create a design idea in the ecoCampus design interface. Fig. 3 shows the design interface with an example curtain wall bay design already created. The right side of the screen included a variety of possible building materials that students could select in their wall design. After a user would touch a particular material, it would become active and they could touch predefined, blank squares on the curtain wall template. After they touched a blank square, it would be assigned the active material and rendered accordingly. As students experimented with designs, they could select alternate materials and override the materials selected in prior design iterations with the new desired materials.

Fig. 3: The ecoCampus design interface allows for touch-based design of possible building components.

After a student was satisfied with his or her design, he or she could view the model in the context of the existing space. When a user selected “View Model”, the screen would change from the ecoCampus design interface to a live camera view of the physical building space. A user would then hold the computing device so the camera would point toward the printed fiducial marker placed on the existing wall and a virtual representation of their design would be displayed over top of the existing wall at full scale. Fig. 4 shows the design from Fig. 3 overlaid on top of the existing wall. In this AR mode, a user could physically navigate around the space and the virtual wall would reorient its position in real-time to provide the illusion that it was already constructed. The only constraint related to a user’s physical position was that the printed fiducial marker would need to remain entirely in view at all times for scaling and orienting the virtual content. If the marker would go out of view, the model content would disappear until the marker came back into view.

Fig. 4: ecoCampus users can view full-scale, virtual mockups of their designs with AR.

After a user visualized his or her virtual design in the AR interface, he or she could proceed to the summary interface to receive tailored performance feedback about the design from ecoCampus. Feedback is generated about the upfront cost of a design on the whole as well as the cost for each individual building material that was selected for the design. The R-value of the building assembly is also provided to the user for a given design. Lastly, users receive design critiques from 3 virtual project participants. The first virtual project participant was a building owner concerned with initial project cost. This critic would generate comments about a design based on the total calculated upfront cost of the design. Based on different threshold values, the owner’s comments would range from greatly satisfied to greatly dissatisfied. The second project critic was a lighting engineer concerned with the amount of daylight that would be allowed to enter the built space with a given exterior wall design. This critic’s comments would be generated based on threshold values for the exterior wall design’s window to wall ratio. If little or no glass would be used in a design, the lighting engineer would be strongly dissatisfied. As students would incorporate additional glazing into their design, the lighting engineer would become more satisfied in their comments. After a certain window to wall ratio threshold was reached, the marginal benefit from additional glass diminished and the lighting engineer’s comments would begin to decline. The third virtual critic was a mechanical engineer who was concerned with lifecycle cost of heating and cooling a space with a particular design based on the R-value of a particular design concept. This critic’s comments would range from highly satisfied to highly dissatisfied based on where the design’s calculated R-value fell in a range of threshold values.

After examining the generated feedback about a particular design, students were able to view a numerical score for their design. The score they received was based on cost, R-value, and the positive or negative comments received from the three project critics. The lower the initial cost, the higher the calculated R-value, and the more positive the comments received by the virtual critics, the higher their final score would be. This numerical scoring mechanism was developed to help students recognize the importance of weighing different project participants' desires in quantifying design performance and also for quickly comparing different design iterations. Fig. 5 shows the ecoCampus simulation game interface with all of the performance values and design critiques.

Fig. 5: The simulation game in ecoCampus allows for tailored feedback to be generated for a user based on a specific design's performance characteristics.

2.3 ecoCampus Technical Specifications

ecoCampus was developed on a mobile computing platform to allow users to design building components in a simple drawing interface, view and physically explore a full-scale virtual prototype in the context of the existing building, and receive tailored feedback about their designs. The Apple iPad (3rd generation) was selected as the mobile computer interface to use for this initial version of ecoCampus because of the built in cameras and the simple touch screen interface on iOS devices. Unity game engine was strategically chosen for development of the ecoCampus graphical user interface (GUI) because it allows for the application to be exported to both iOS and Android platforms as well as other console game system formats. From a development perspective, this provided freedom for future versions to be easily adapted to include additional content for a variety of mobile computing and smartphone platforms. In addition to the exporting benefits that Unity offered for development, there are also several external parties who develop plug-ins for Unity. For this work, String provided an easy method for creating custom fiducial markers with pre-defined scripts to allow Unity cameras to track the custom markers. This allowed for real-time physical navigation of a space to see augmented content. The simulation game component of ecoCampus was developed within Unity using construction cost data and typical R-values for different building materials to automate performance feedback for ecoCampus users.

3. RESULTS

During this ecoCampus implementation, 47 students participated in the study. Of these 47 students, 30 were male and 17 were female. All but one of the participants was a college freshman. Students were also surveyed to find out their intended majors. In this semester, 67% of the students indicated that they were interested in pursuing architectural engineering as their major. After analyzing the submitted files from all of the students, several interesting findings were observed.

The screen captured images of the students' designs were examined to identify how many design iterations students explored during the activity. For each student who used ecoCampus, the number of different design iterations that they completed was documented. It was found that students completed between 5 and 19 different design iterations with a mean of 9.3 design iterations during the class session. The number of design iterations created by the students who used ecoCampus was compared to the number of iterations created by students who completed the activity with the purely open-ended version where they were only supplied with blank sheets of paper (Ayer et al. 2013b) and also the image-based version where students were supplied with images of the existing building and a basic materials list to help them illustrate their designs (Ayer et al. 2013a). The number of iterations with ecoCampus was significantly higher than both prior activity formats ($p<0.001$). Fig. 6 shows the percentage of students in each treatment that explored a given number of design iterations in the same time period.

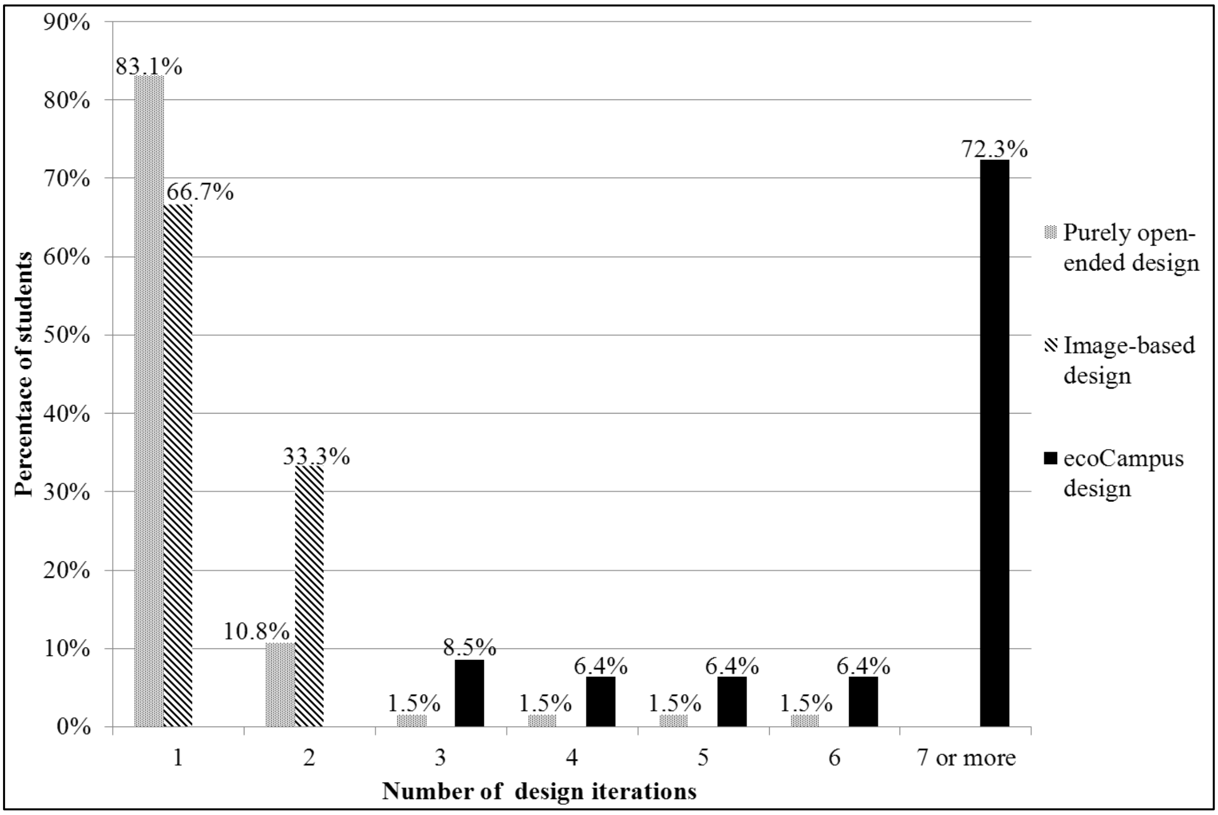


Fig. 6: Graph showing the number of design iterations for each of the experimental treatments.

In addition to examining the number of design iterations that were explored by students during this design activity, it was also of interest to examine how many different building materials students considered during their design process. It was noted in prior implementations that students generally did not deviate from the existing building design with regard to material selection and geometric layout when attempting to create their more sustainable design idea (Ayer et al. 2013b). On average, students who used ecoCampus used 9.2 different materials throughout their design creation process, which is substantially more than the 3 main materials currently used on the existing section of curtain wall. This was also significantly more than the number of materials that students used in prior semesters with paper-based formats ($p<0.001$). The numbers of materials that students experimented with in their design processes from the different activity formats can be seen in Fig. 7.

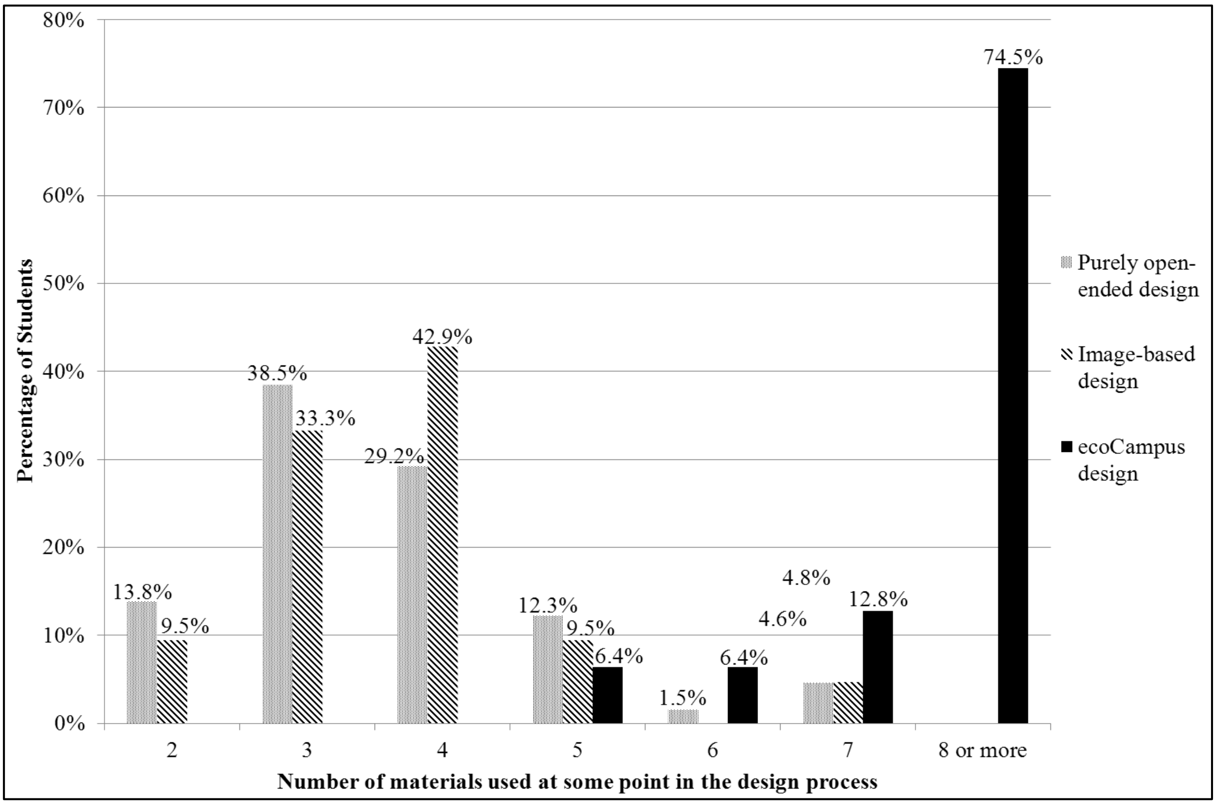


Fig. 7: Graph showing the percentage of students who experimented with certain number of materials throughout the design process.

In addition to analyzing the designs that were submitted, the responses to pre- and post-test questions from this work were examined to understand the learning and perception that the activity made on the students. Students generally felt that the format of ecoCampus was effective, with only 6.4% of students reporting it as either “not very effective” or “not effective at all.” Students generally also found the activity to be interesting. For example, 63% of the students felt that it specifically increased their interest in sustainability and 70% indicated that it made them more interested in the building design process.

After completing this initial study some unintended learning outcomes were also observed. For example, as students were designing in ecoCampus, they frequently tried to achieve the highest score possible. While this might initially sound like a good approach, in this initial ecoCampus version, the only factors that affected the score were initial cost, daylight usage, and thermal efficiency. While these are certainly important considerations when designing an exterior wall for this project, it excluded other important design considerations, such as constructability and aesthetics of the design. In striving to achieve the highest score possible, students could overlook impacts from aesthetics or constructability. This is not to say that every student overlooked these other design considerations. One student mentioned, “I liked the activity. It was challenging using good insulating materials and keeping the interior aesthetically pleasing at the same time.” This may be an area where further development will help to encourage all users to consider other design considerations while developing their wall concepts.

4. CONCLUSIONS AND FUTURE WORK

This work has examined the educational benefits of using augmented reality in conjunction with a simulation game to educate students about sustainable design practices in the built environment. In this paper, ecoCampus has been presented as a new application that allows students to experiment with several “what if” scenarios, visualize full-scale virtual mock-ups of their design, and receive tailored feedback about their design ideas. To test ecoCampus, students were given a hypothetical design scenario where they were asked to redesign an exterior wall on an existing LEED rated building to attempt to make it perform even more sustainably. After analyzing the submitted design files, several noteworthy findings were observed.

Students completed this activity through the creation of several different designs. Students who used ecoCampus to create their sustainable building created between 5 and 19 different design ideas over the course of the 40-minute design period, which is significantly more than prior semesters where students were not provided with the ecoCampus platform in which to design. This suggests that this type of mobile game environment can serve as a catalyst to encourage students to brainstorm different design possibilities without the need to explicitly instruct students to complete a given number of alternate design ideas. This may be beneficial because students frequently fixate on a particular idea, which can limit their ability to consider other, possibly better design ideas (Jansson & Smith 1991; Linsey et al. 2010).

The students who used ecoCampus also considered more possible building materials in their design process as compared to prior semesters' students where the application was not used. This could be due in part to the fact that some first-year students are not yet aware of possible different building materials that could be used in a design. The provided options eliminate the need for students to identify possible choices on their own. While this finding may not necessarily suggest that students are more *willing* to experiment with different building materials with ecoCampus, it does suggest that they are more *able* to experiment with different materials. For future educational game development, this may be especially beneficial for design modules where laypeople cannot realistically be expected to know all possible design options that might be relevant to a given design challenge.

This research has identified benefits that were observed through the use of ecoCampus with in a first-year architectural engineering class. Future work will also explore possible benefits that can be obtained by introducing this learning tool to students in other, building-related disciplines, including Architecture and Civil Engineering. Additionally, the ecoCampus prototype will be further developed to include more virtual design critics to the simulation game interface to encourage every student to consider even more design considerations in their process. This will likely make the application more challenging, but also more realistic in complexity. Finally, it will be of interest to test the students who used ecoCampus later in their academic careers to see if the brainstorming behaviors they displayed in ecoCampus are translated to other courses and design projects as well or if, without the use of ecoCampus, students are prone to design fixation. This future study could examine students' design processes in other courses and compare the number of ideas generated between those who had completed the ecoCampus design activity and those who had not.

5. REFERENCES

Ayer S.K., Messner J.I. and Anumba C.J. (2013a). Assessing the impact of using photographic images to influence building retrofit design education, Proceedings of the 2013 architectural engineering institute conference, University Park, PA, USA.

Ayer S.K., Messner J.I. and Anumba C.J. (2013b). Challenges and benefits of open-ended sustainable design in first year engineering, *Submitted for publication*.

Bernstein H.M. (2010). Green BIM how building information modeling is contributing to green design and construction, McGraw Hill Construction SmartMarket report, Bedford, MA.

Dede C. et al., (1999). Multisensory Immersion as a Modeling Environment for Learning Complex Scientific Concepts, In N. Roberts, W. Feurzeig, & B. Hunter, eds, *Computer modeling and simulation in science Education*. New York.

Finke R.A., (1990). *Creative imagery: Discoveries and inventions in visualization*, Hillsdale, NJ.

Finke R.A., Ward T.B. and Smith S.M. (1996). *Creative cognition: Theory, research, and applications*, Cambridge, MA.

Gredler M. (1994). *Designing and evaluating games and simulations : A process approach*, Houston, TX.

Jacobs J.W. and Dempsey J. (1993). Simulation and gaming: fidelity, feedback, and motivation, *Interactive instruction and feedback,* Englewood Cliffs N.J.

Jansson D.G. and Smith S.M. (1991). Design fixation. *Design studies*, Vol 12, No. 1, 3–11.

Juul J. (2003). The game, the player, the world: looking for a heart of gameness, Proceedings of level up conference, University of Utrecht, 30–45.

Lave J. & Wenger E. (1991). *Situated learning: Legitimate peripheral participation*, Cambridge, UK.

Linsey J.S. et al. (2010). A study of design fixation, its mitigation and perception in engineering design faculty, *Journal of Mechanical Design*, Vol. 132, No 4.

Milgram P. and Kishino F. (1994). A taxonomy of mixed reality visual displays, In *Transactions on Information Systems,* 1321 – 1329.

National Academy of Engineering (2004). *The Engineer of 2020: Visions of engineering in the new century*, Washington, D.C.

Prensky M. (2004). The Seven Games of Highly Effective People, *Microsoft Games for Windows*.

THE SITUATION ENGINE: A HYPER-IMMERSIVE PLATFORM FOR CONSTRUCTION WORKPLACE SIMULATION AND LEARNING

Sidney Newton, Russell Lowe, Rosamond Kember, Rui Wang and Stephen Davey
The University of New South Wales, Australia

ABSTRACT: *The prospect of being able to place an individual within an entirely interactive, simulated environment has long been held, but only recently is it being realized. Flight simulators were the first to provide a hyper-immersive experience using a combination of very detailed and accurate models of aircraft systems, high-resolution visualization and motion platforms. More recently, advanced video game technologies have been coupled with augmented reality systems and sophisticated tracking technologies to provide hyper-immersive experiences of battlefield conditions, crime scenes, operating theatres, industrial processes, etc. A key problem for developers of any hyper-immersive environment is the significant overhead costs of modeling, programming, display technologies and motion simulation.*

The Situation Engine is an application platform that provides for specific and managed building and construction experience to be made available using low-cost, advanced digital technologies. The same engine can drive a multitude of learning situations. Multiple users collectively occupy the same simulated workplace but experience that situation individually by individual movement through the space. Head tracking, gesture recognition, voice communication, 3D head-mounted displays, location-based sound and embedded learning resources have all been incorporated into the Situation Engine at minimal cost. The total enabling technology cost per participant is currently around $600 Australian.

This paper will focus on the hyper-immersive nature of the Situation Engine. In particular, the distinction between immersion (as a quantitative measure of sensory fidelity) and presence (as a qualitative perception of 'being there') will be articulated and clarified. The paper also highlights one of the various ways in which hyper-immersion is manifested in the Situation Engine: gestural control. Gestural control has been implemented using a Microsoft Kinect™ and proprietary gesture detection algorithms to monitor a range of gestures in parallel, including gestures that are context dependent.

KEYWORDS: *Simulation, Hyper-Immersion, Cost, Situation Engine, Gestural Control.*

1. CONSTRUCTION WORKPLACE SIMULATION AND LEARNING

Programs of study in the higher education sector are being shaped increasingly by the imperative of employability. A recent review of graduate employability in Australia highlighted the need to provide students with effective "exposure to professional settings" (Cleary *et al*, 2007:10). A national framework for addressing employability skills in Australia subsequently characterised the individual performance requirements in terms of their ability to: "work with increasing levels of autonomy; cope with increasing complexity and uncertainty; and adapt with increasing ease and effectiveness to unfamiliar contexts". (Goodwin *et al*, 2012:15). The focus on employability is casting new light on the broad notion of practice-based experiences, the higher cognitive levels of learning and how this all might best be integrated into higher education programs of study (Billett and Henderson, 2011). Practice-based experiences include such activities as practicums, industry placements, case studies, role play and site visits.

An effective practice-based experience is one in which the learning outcomes are realised in terms that are both deliberate and intentional (Washbourn, 1996): deliberate in the sense that the process of learning is managed effectively and controlled from a pedagogical perspective; intentional in the sense that the particular skills to be developed through that experience are made explicit, can be demonstrated by the student and are assessable. However, the many practice-based experiences that do provide for explicit student development and assessment also tend to be problematic when it comes to exercising control. For example, an industry placement can develop

Citation: Newton, S., Lowe, R., Kember, R., Wang, R. & Davey, S. (2013). The situation engine: a hyper-immersive platform for construction workplace simulation and learning. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

important practical skills but the resources required and opportunities available to target particular skills are often prohibitive. Those practice-based experiences that might lend themselves to more direct control also tend to be more abstract in their learning outcomes. For example, a case study can be selected carefully to address a particular issue or skill but does so vicariously or once removed from the actual activity itself.

The current context of higher education in Australia, as it is elsewhere, is one of broadening access and participation in a climate of structural and organisational change (Bradley *et al*, 2008). Higher education must cater for increasing numbers of students and do so with a tightening of the available resources. In that context the integration of effective practice-based learning is increasingly problematic. The potential for practice-based learning to be exercised using relatively inexpensive and scalable new simulation and learning technologies is a compelling one. This paper will describe the technical configuration and functionality for a new concept in simulation and learning technology, The Situation Engine. The Situation Engine is an application platform that provides for specific and managed building and construction experience to be made available using low-cost, advanced digital technologies.

2. THE SITUATION ENGINE

We define the Situation Engine as:

"An application that provides for specific and managed practical building and construction experience to be made available to students through advanced digital technologies."

Figure 1 begins to un-wrap this definition in more functional terms. Each specific situation is comprised of: certain environmental conditions (weather, time, location, etc.); objects and their properties (buildings, equipment, materials, etc. with dimensions, mass, movement, density, etc.); actors and their behaviours (characters, interfaces, avatars, etc. with behaviours, scripts, intelligence, etc.); and data feeds (web, video, motion, devices, etc.). Various combinations of environments, objects, actors and feeds constitute a particular situation. Each situation is then articulated as a series of interactions. The interactions are not prescribed, but rather emerge from the basic physics and decision-making that governs the behaviour of environments in certain conditions, objects with certain properties, actors with certain behaviours and feeds with certain data manipulation. Howsoever the complex interactions resolve themselves at any given moment in time, is then rendered to the user as a display of some form (screen, goggles, digital cave, 3D, soundscape, etc.). The user interface needs to deliver an immersive, first-person experience of the situation to the user as it unfolds. The more realistic the immersive experience the better Bystrom *et al* (1999). First-person engagement is critical to an immersive experience in this context, as the specific situation is then presented as a person would typically engage with the world. Clearly, the same Situation Engine is intended to drive a multitude of tailored learning situations.

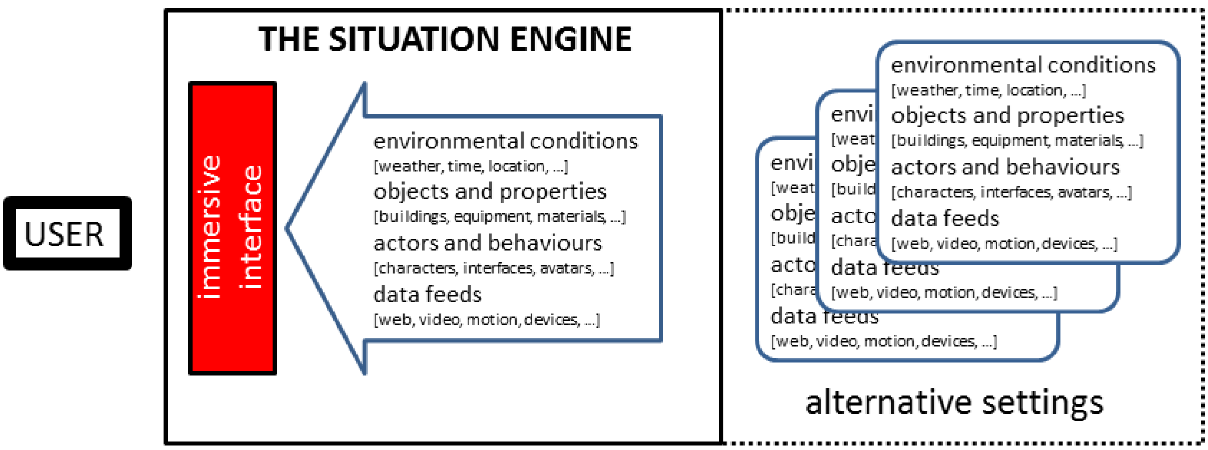


Fig. 1: Concept Structure for a Situation Engine

The target curriculum for the current Situation Engine development is the 1st year course of a 4 year program of undergraduate study in construction management and property in Australia. The course is the first in the program of study to introduce students to construction technology. It deals with the functional requirements and construction methods specific to residential/domestic construction typical in Australia. As such the course examines a range of key technical aspects, including: brick and timber frame construction methods and materials; domestic joinery; staircase construction; finishes; plumbing, drainage and electrical services; methods of setting out and supervision. The course also involves developing skills in on-site observation and the production of housing site reports.

A formal process of human factor analysis using focus groups and task analysis has been undertaken, along with an analysis of the learning needs of current students (Newton, 2012). For instance, the learning needs were assessed by reviewing the performance of several hundred students in their end-of-year examinations, to identify those topics where students were having problems and the typical mistakes they were making specific to construction technology. A small reference group of users has been established to trial prototype systems and evaluate various implementations. Formal evaluation of the system is ongoing.

3. A HYPER-IMMERSIVE PLATFORM

The most sophisticated interactive virtual reality simulation environments with practical application to teaching and learning are to be found in video games. Of particular relevance is the recent emergence of providers making the game engines themselves (the kernel of coding used to drive a collection of actual game implementations) available on an open-source basis. The most powerful game engines are now typically free to acquire for teaching and learning purposes, they allow third party modifications and are supported online by a significant and committed community of users and developers. The Situation Engine has been implemented using the proprietary video game engine CryENGINE®3. This engine features easily the most advanced graphical, physical and animation technologies available (see: http://www.crytek.com/cryengine).

The quality of the visual rendering in CryENGINE®3 is illustrated in Figure 2, which is a screen grab from the current implementation of The Situation Engine. It shows a situation where the construction project has progressed through excavation, foundations and is nearing completion of timber framing. The site shows various workers, plant and equipment, facilities and materials – as seen through the eyes of the user avatar. The same site can be used to present alternative situations, at different stages of construction, with different activities and other configurations of material storage, signage, waste management, security, etc. Multiple users can be represented and experience the situation collectively. At various points a user can interact with the building as it is constructed – checking the placement of reinforcement and formwork just prior to pouring the slab, for example. Users get to see how the work at different stages of construction has been prepared, measure and check sizes and distances, assess details against building codes and best-practice guides, etc. Assessment tasks can test a students' understanding of related issues, such as safe work practices, material storage and handling considerations, site security, environmental protection, wet-weather hazards, noise pollution, etc.

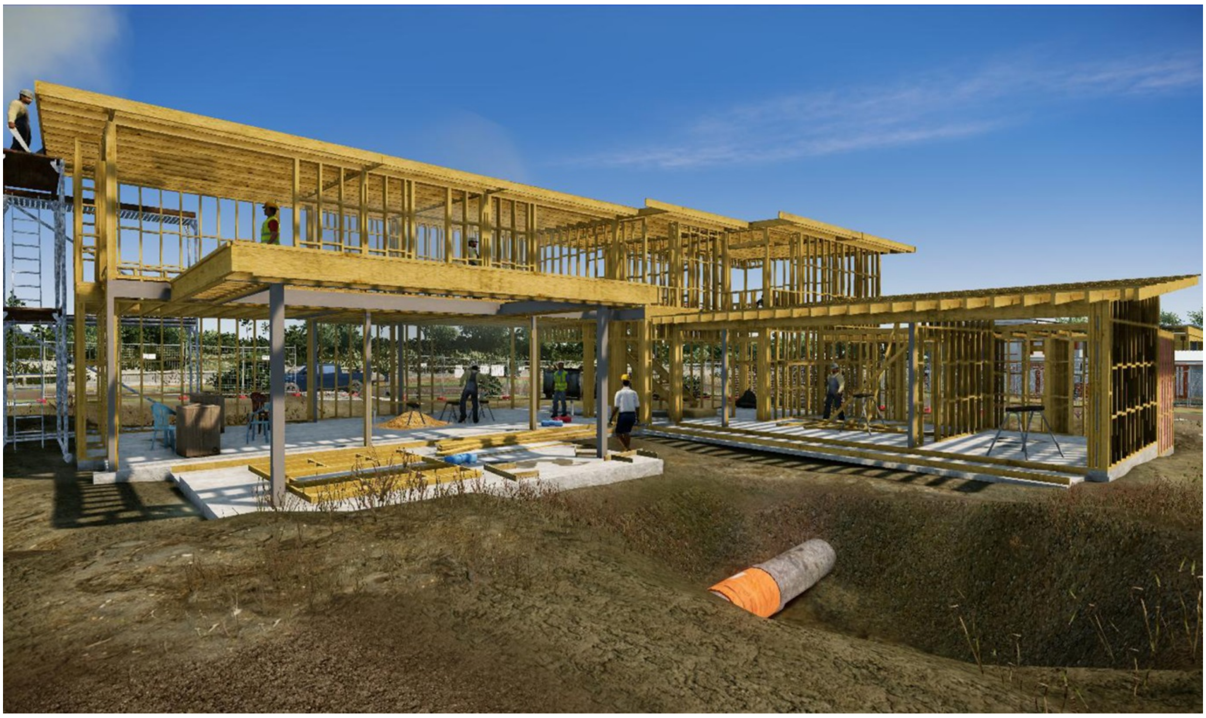


Fig. 2: Screen Capture of Construction Site Rendering in The Situation Engine

Immersion is a critical feature of virtual reality simulation. Slater and Wilbur (1997) define immersion as “an objective description of aspects of the system such as field of view and display resolution”. The term is still used to refer to the quantifiable aspects of display technologies (such as vividness, resolution and display dimensions). With advances in virtual reality technologies and the blurring of display with other aspects of the virtual reality simulation, immersion is now also used to refer to a broader compass of representation technologies, including the self-representation of the user/avatar, the physics of the models, the sound quality, etc. This broader range of immersive qualities is critical because they each contribute to a users’ overall sense of presence.

In contrast to immersion, presence is used to refer to the subjective phenomenon of ‘being there’ (Heeter, 1992). Presence is a product of the mind and independent of any specific type of technology or technological context. A greater sense of presence is often associated with improved user performance (Bystrom *et al*, 1999).

The relationship and distinction between immersion, presence and performance can be confusing, as the terms are often conflated in the literature. Figure 3 seeks to clarify the meanings used in this paper. In this model, the level of immersion is solely determined by the technical qualities of the virtual reality simulation technology. The better the quality of the rendering, the way objects behave, the soundscape, the currency of the information, the social interaction, bodily engagement, haptic feedback, etc., the greater the level of immersion. But the measure of immersion is expressed entirely in technical terms of frame rate, resolution, lag, frequency, etc. What Bystrom *et al* (1999) refer to as the ‘sensory fidelity’ of the technology.

Beyond a measure of the sensory fidelity is the sense of presence experienced by a user. It is generally presumed that a greater sensory fidelity will lead to a greater sense of presence, but the issue is more complex (van den Hoogen *et al*, 2009). Steuer (1992) notes that in addition to the sensory fidelity (what he refers to as the vividness and interactivity measures of a virtual reality) the sense of presence will be directly influenced by the individual characteristics of the user and the particular task activity in which they are engaged at the time. In other words, the cultural and experiential background of the user and the purpose and process with which they employ a given virtual reality simulation will significantly influence the sense of presence they perceive.

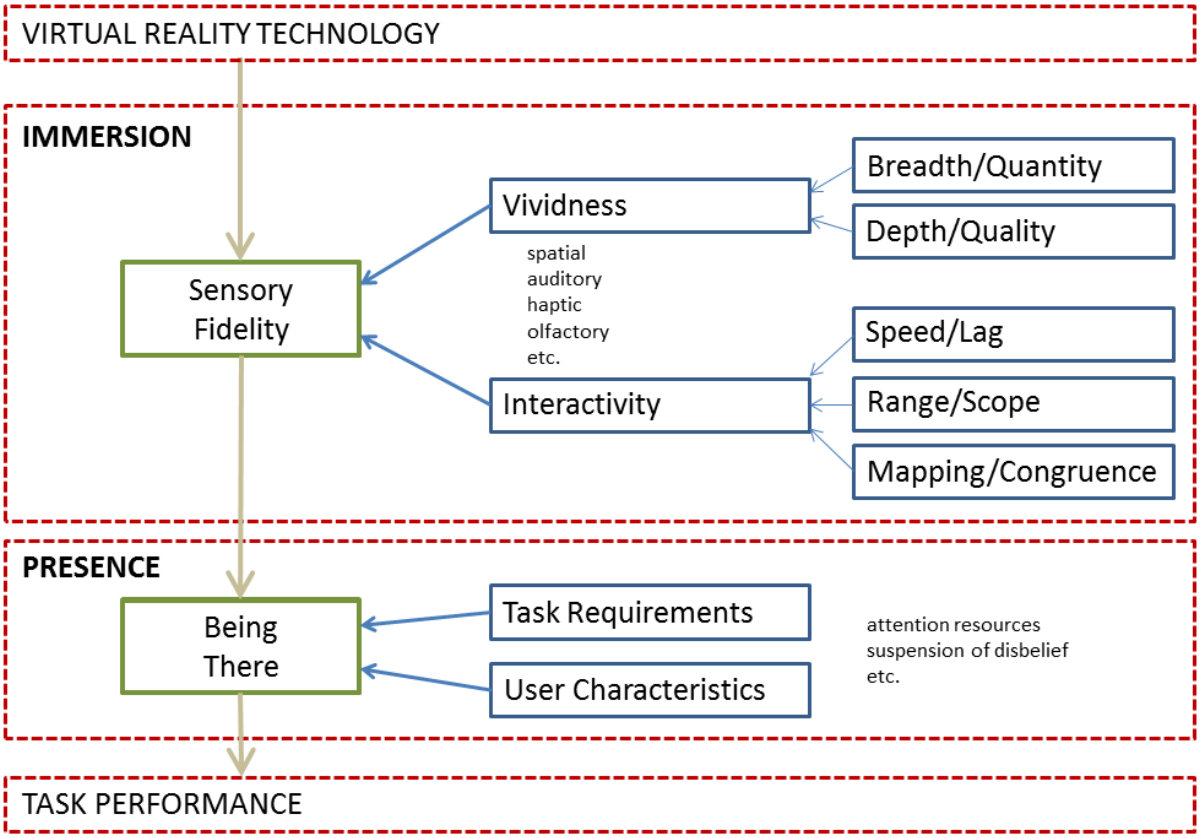


Fig. 3: Elements of Immersion and Presence (adapted from Steuer, 1992 and Bystrom *et al*, 1999)

Notwithstanding the complicating nature of presence on immersion, or other things being equal, increased levels of sensory fidelity do equate with increased immersion. A hyper-immersive platform is defined here as "a virtual reality simulation system where the fidelity of the various sensory channels is maximized within current technical capacities". That is to say, spatial modeling provides near-photorealism for indoor and wide-open outdoor environments, auditory modeling provides 3D locational sound reproduction and syncronised voice animation, haptic modeling includes full body tracking and gestural control, etc.

For example, in terms of bodily immersion the Situation Engine has been developed to enable the user to control the behavior of their avatar in the system using bodily movements. Control of this kind is termed 'gestural control'. Gestural control is an important aspect of immersion because gestures are often more intuitive for users, particularly those inexperienced with established gaming interface technologies. Gestural controls have the significant advantage over traditional controls (such as keyboard and mouse) because they can map user actions directly to their congruent actions in the virtual world – a swing of the user arm equates with a swing of the virtual arm. Key issues for the development of improved gestural control relevant to the Situation Engine include:

(i) The need for low latency, real-time interactivity. This is required to ensure that gestures are interpreted into actions in the virtual environment with the same immediacy as for real-world actions. This required working directly with the base-level coding and software development tools.

(ii) Design of the gesture detection algorithm to recognize and interpret natural gestures appropriately. This required careful filtering of, and focus on, relevant body parts to reduce the total computation load. For example, many gestures could be limited to tracking and analysis of the upper arm and forearm movements only.

(iii) Capacity to perform multiple gestures in parallel. Walking, turning, leaning and swinging a hammer, are all possible at the same time in the Situation Engine's gesture control system. The system monitors body movements for all and any registered gestures in parallel.

The Microsoft Kinect™ provides skeletal tracking data for 21 virtual bones, including head, arms, legs, hips, neck, and spine. The skeletal framework is approximated to fit the body of the user as it is scanned for shape and depth.

Data on the movement and position of each virtual bone is parsed in real-time by specially developed detection algorithms, which interpret sequences of movement into registered gestures. Gestures currently detected include turning, jumping, leaning in any direction, moving at gesture-controlled speeds on a smooth and continuous spectrum from walking to running. More sophisticated, context-dependent gestures are also monitored - reaching out with the hand to open a door, entering the cab of an excavator or grabbing a small hand tool, for example. Further gestures are being added, with the intention to exhaustively yet efficiently map a full compass of potential user actions.

To implement the gesture control system required basic modification to the CryENGINE®3 base-level coding (C^{++}). A multiplexer class was created such that data retrieved from the Microsoft Kinect™ could be served out to an arbitrary number of gesture detection algorithms with minimal impact on memory footprint and real-time performance. Gesture detection algorithms were implemented at the higher level as nodes in the CryENGINE®3 control flow graph (CFG). This provided ready access to gesture detection, as and when required. It also defined the related actions in the virtual environment that each gesture was intended to initiate.

Various other modifications and supplements to the immersive technologies in CryENGINE®3 have been developed to create a hyper-immersive environment. However, the abiding issue with any hyper-immersive virtual reality simulation is the associated costs. By way of context, the video game industry has now overtaken the film industry in terms of its overall investment and revenue values. Several “Call of Duty” titles, for example, have grossed over 1 billion dollars. The most recent release, "Black Ops", grossed that amount in just the 6 weeks following its release (see: http://www.vgchartz.com/article/250163/call-of-duty-a-sales-history/). In such a context it is hardly surprising perhaps that the budgets for developing hyper-immersive commercial games are also very large. Indeed, the development budget for “Black Ops” is believed to have been between $18-20 million, with an associated advertising and marketing campaign somewhere in the order of $250 million (see: http://agreatbecoming.com/2011/02/08/call-of-duty-black-ops-return-on-investment-is-4350/). How might the development costs for serious simulations be contained to anywhere near a more feasible level?

4. COSTS AND RESOURCES

The Situation Engine was developed with modest funding from the Australian Government Office for Learning and Teaching as a teaching project initiative. As a non-commercial development, the project was able to make use of the free TDK download of CryENGINE®3. This left the majority of direct development costs specific to the creation of environmental content. Content can broadly be split into two main categories: 3D models and 2D textures. 3D models include the visible geometry and collision volumes (required for physics calculations). 2D textures include the full complement of texture definition files needed to render specific materials (it is not uncommon to have diffuse, normal, detail, specular and bump maps all operating in concert to convincingly represent a material), particles and clouds (such as water, smoke and even insects), images and decals (overlay textures that are used to give basic character to surfaces or for labels and signage) and for various elements of the user interface. Costs for environmental content was kept to a minimum by, as far as was practical, modifying the existing game assets available from the gaming community and other online resources. Hundreds of unique characters, avatars, vehicles, construction equipment, building materials, signage and building elements were created in this way. However, given the need to represent authentic Australian construction practices and building codes, a significant effort was involved in the creation of tailored building elements and construction details. These were typically drafted using Sketch-Up® and Autodesk® 3ds Max® specific for the game engine, imported and textured. A range of leading community modeling and texturing software is supported directly into CryEngine. Alternative transfer protocols are supported using XML-based schema such as COLLADA™ (see: https://collada.org/). The full development workflow is illustrated in Figure 4.

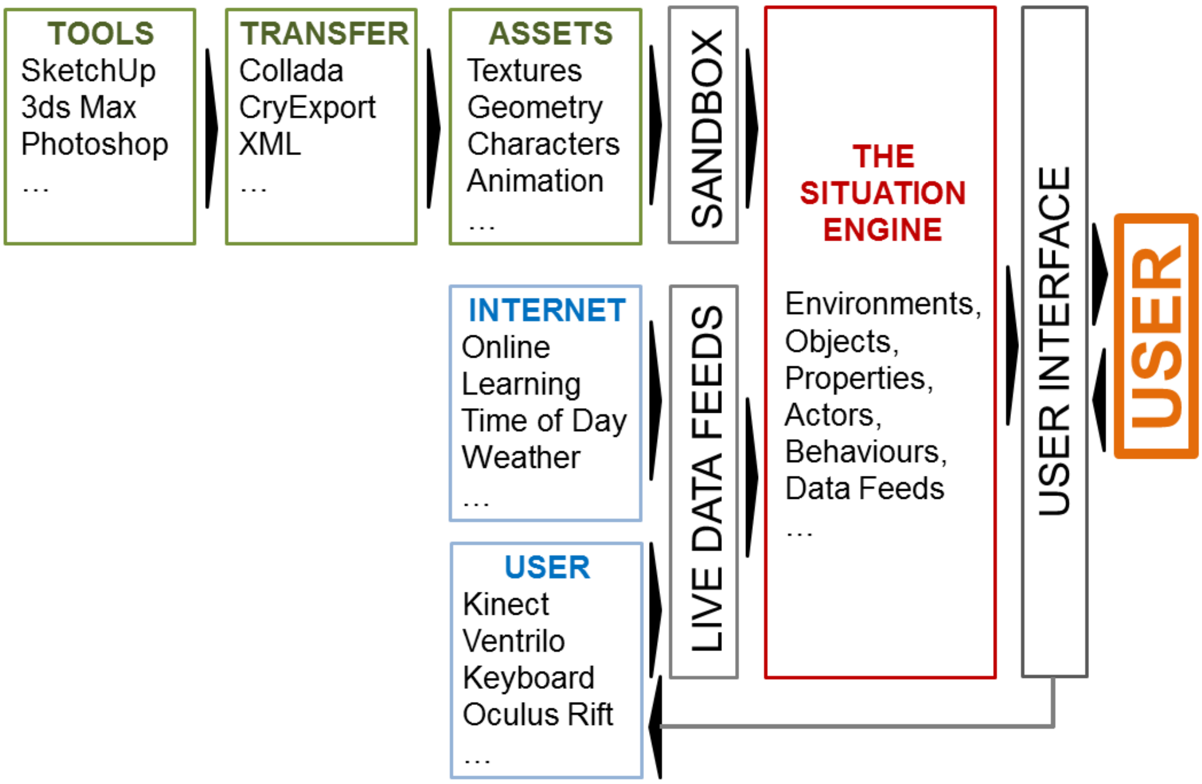


Fig. 4: Schematic of the Development and Deployment Workflow for The Situation Engine

Once the content has been modeled it must be animated and the interactivity defined. In the case of CryENGINE®3 the control of objects, agents and interactivity is managed using a system of control flow graphs (CFG's). The CFG is a visual representation, using graph notation, of the relationships and connections between different entities and events in the game. They define the routes available during execution by specifying how each individual entity or event will respond to given input or context variables. In a similar manner to visual programming, CFG's provide sophisticated programming capability without the need for specific programming language expertise. The WYSiWYP (What You See is What You Play) functionality in CryENGINE®3 is called 'The Sandbox', which provides full game authoring capabilities at a high level of definition. Functionality such as this has enabled the Situation Engine to be developed by non-computer scientists. Indeed, much of the development has been achieved by current undergraduate and recent graduate students in Architecture and Architectural Computing. Our estimate of the total time taken to develop the current Situation Engine implementation is 1-2,000 person hours, or somewhere around $50K. That does not include the supervisor time or time spent developing previous implementations, but is a reasonable measure of the effort required to progress from a blank, flat site to a fully operational, complex and accurate situation where all of the building content was modeled from scratch, based on actual construction drawings.

The development costs of each Situation Engine implementation may be relatively small compared to commercial block-buster games, but might still be prohibitive. Our experience in making the current system available to other academics has been that individuals tend to have a strong preference to tailor their student interaction to meet specific needs in particular ways. Two further resourcing efficiencies have been achieved:

(i) For staff or students with a basic technical competence in video game development (even basic CAD modeling skills), much of the existing content can be reused and modified through recombination and parametric adjustment. For example, the standard character available in CryENGINE®3 is a combat trooper. The standard character has over 130 default animations and movements available. It is possible to create or purchase at very low cost a huge range of custom meshes and clothing that can be simply added to the standard character rig (skeleton) to take advantage of the default movements available (see: http://www.the3dstudio.com/). Every characteristic imaginable, skin colour, gender, clothing, age, height, hair, etc., can be varied using the same standard character rig. Similar modifications can be made to existing vehicles to create entirely new forms of transport. For example, we have modified the standard military tank to look and perform as a hospital wheelchair.

(ii) For staff with no competence or interest in video game development, the same situation can be utilized in a variety of ways to teach a variety of topics – from construction technology to health and safety to site management. For each of these topics the situation can be the same, but the student interaction does need to be directed and supported differently. A recent innovation has been to incorporate live access to the internet using standard browser technologies placed in various locations within the situation – the browser can be mapped onto a computer or tv screen model located in the situation, or be a pull-down option available to the user at any point in time or location. Users (students) can interact with these browser windows from within the game with full browser functionality. This means that staff can set tasks, monitor progress, provide links to resources and generally provide online teaching support directly into the Situation Engine, using standard online teaching technologies. Staff need only tailor their online teaching resources to fundamentally alter the student experience of the particular situation, without ever having to modify the Situation Engine itself.

More generally, the cost of deployment of the Situation Engine is also falling. The cost of computer hardware required to run the system is difficult to estimate as CryENGINE®3 provides a range of native ports to a variety of platforms from Xbox 360™ and PlayStation®3 to standard PC laptops, workstations and remote access grid arrays. Whilst the licenses required to port to Xbox 360™ and PlayStation®3 are themselves prohibitively expensive, because they presume a commercial application, that possibility puts the purchase of entry-level technology at potentially about $300. Even cheaper and more powerful cloud computing is already revolutionizing gaming, and is only limited by the download/upload connection speeds. Associated functionality is also becoming very inexpensive. For example, Oculus VR™ are currently shipping development kits for a head-mounted display (the 'Rift') that provides exceptional field of view characteristics with very low-latency (see: http://www.oculusvr.com/). The Rift has an anticipated retail price of $300. We utilize the Microsoft Kinect™ to recognize gesture controls and track the physical movement of the user in their space to move virtually through the Situation Engine environment. This retails separately at around $140, or comes bundled with the Xbox 360™. When using the multi-player mode to collaborate with other users, we utilize the Ventrilo surround sound VoIP (Voice Over the Internet Protocols) group communication software (see: http://www.ventrilo.com/). This application is free. The current Situation Engine implementation, developed with Australian Government funding, is provided free of charge under a Creative Commons Attribution 3.0 Australia license (see: http://creativecommons.org/licenses/by/3.0/au/). The potential collective baseline cost of all enabling technologies and equipment per user, for the full scope of functionality, is therefore around $600. The full scope of potential functionality and various downloads can be reviewed/accessed at the Situation Engine website (see: http://www.be.unsw.edu.au/programs/situation-engines/).

5. CONCLUSIONS

Given a growing focus on employability and the need that such a focus lends to providing more substantive and more effective practice-based experiences to students, this paper describes the technical configuration and functionality for a new concept in simulation and learning technology – The Situation Engine. The Situation Engine provides for specific and managed practical building and construction experiences using advanced video game technologies. Each situation comprises a dynamic combination of environmental conditions, objects and properties, actors and behaviours and external data feeds. The current implementation of the Situation Engine is specific to residential/domestic construction technology, characteristic to Australia. It provides a hyper-immersive virtual reality simulation of a residential building project at various stages of construction, from excavation through foundations, timber framing and finishes to fitout.

The focus of this paper has been on the hyper-immersive nature of the Situation Engine: how immersion is defined and how it is realized. In particular, the distinction between immersion (as a quantitative measure of sensory fidelity) and presence (as a qualitative perception of 'being there') has been articulated and clarified. The paper has highlighted one of the various ways in which hyper-immersion is manifested in the Situation Engine: gestural control. Gestural control has been implemented using a Microsoft Kinect™ and proprietary gesture detection algorithms to monitor a range of gestures in parallel, including gestures that are context dependent.

An abiding issue with any hyper-immersive simulation technology, especially those developed for teaching and learning, is cost. A schematic of the development and deployment workflow for The Situation Engine is presented that supports particular resource efficiencies. Our estimate of the total time taken to develop the current Situation Engine implementation is in the order of 1-2,000 person hours, or somewhere around $50K. Such development costs are trivial in the broader context of commercial video game development, but may still be prohibitive. Two particular resourcing efficiencies are described that reduce the potential burden of development further: direct development of a situation by modification and indirect development by tailoring online teaching and learning resources. Finally, consideration is given to the baseline cost of deployment. A very near future baseline figure for all enabling technologies and equipment per user is in the order of $600.

Hyper-immersive virtual reality construction workplace simulations are now available at very reasonable development and deployment costs. The quality of the simulations is such that broader development offers significant potential to address the growing issue of how workplace experience can usefully and efficiently be provided to large cohorts of students. The Situation Engine marks genuine progress towards that potential.

6. ACKNOWLEDGEMENTS

Support for this research has been provided by the Office for Learning and Teaching (OLT), an initiative of the Australian Government Department of Education, Employment and Workplace Relations. The views expressed here do not necessarily reflect the views of the OLT.

7. REFERENCES

Billett, S. and Henderson, A. (eds) (2011) *Developing Learning Professionals: Integrating Experiences in University and Practice Settings*, New York: Springer.

Bradley, D., Noonan, P., Nugent, H. and Scales, B. (2008) *Review of Australian Higher Education: Final Report*, available: http://www.deewr.gov.au/he_review_finalreport/ [accessed on 30 January 2011].

Bystrom, K-E., Barfield, W. and Hendrix, C. (1999). A Conceptual Model of the Sense of Presence in Virtual Environments. *Presence: Teleoperators and Virtual Environments*, 8(2), 241-244.

Cleary, M., Flynn, R., Thomasson, S., Alexander, R. and McDonald, B. (2007) *Graduate Employability Skills*. available: http://aces.shu.ac.uk/employability/resources/ [accessed on 16 May 2013].

Goodwin, S., McDonald, R., Perkins, K., Wignall, L., Gale, G., O'Callaghan, K., Murray, F., McGraw, J., Redman, K. and Hopwood, J. (2012) *Employability Skills Framework Stage 1: Final Report*, available: http://deewr.gov.au/employability-skills [accessed on 16 May 2013].

Heeter, C. (1992). Being there: the subjective experience of presence. *Presence: Teleoperators and Virtual Environments*, 1(2), 262-271.

Newton, S. (2012) A Situation Engine for Teaching and Learning Residential Construction Technology, in Sulbaran, T. (Ed), *Proceedings of 48th ASC Annual International Conference*, pp.9-17, available: http://ascpro0.ascweb.org/archives/cd/2012/paper/CEUE201002012.pdf [accessed on 23 March 2013].

Slater, M. and S. Wilbur (1997) A framework for immersive virtual environments (FIVE) : Speculations on the role of presence in virtual environments, *Presence-Teleoperators and Virtual Environments*, 6(6), 603-616.

Steuer, J. (1992). Defining Virtual Reality: Dimensions Determining Telepresence. *Journal of Communication*, 42(4), 73-93.

van den Hoogen, W. M., IJsselsteijn, W.A. and de Kort, Y.A.W. (2009) Effects of sensory immersion on behavioural indicators of player experience: movement synchrony and controller pressure. *Breaking New Ground: Innovation in Games, Play, Practice and Theory. Proceedings of DiGRA 2009*. London: Brunel University, pp.1-6.

Washbourn, P. (1996). Experiential learning: Is experience the best teacher?, *Liberal Education*, 82(3), 1–10.

VIRTUAL REALITY FOR MEETING INTERACTION IN INFRASTRUCTURE CONSTRUCTION PROJECTS

Janne Porkka & Timo Kuula
VTT Technical Research Centre of Finland, Finland

Kalle Kähkönen & Jukka Rannisto
Tampere University of Technology, Finland

ABSTRACT: *Urban planning and infrastructure projects of varied sizes are increasingly utilizing model-based applications at planning phase. Although the use of virtual models has its advantages, there are multiple challenges that diminish their potential in project use. These challenges are related to either non-human or human topics. The non-human topics cover issues like deficient processes, practices and tools. The human-related topics include for example lack of communication and interaction between relevant stakeholders. The interaction is a key element in current design practice due to the high number of disciplines involved in design formation and decision-making.*

During the past years, many key stakeholders have experienced difficulties in changing the current way of working with model-based practices. Virtual reality (VR) has been found to offer promise for design visualisation to convey messages with reduced communication difficulties between stakeholders. This paper draws findings from observations in one meeting at an on-going large infrastructure construction project in Finland. In this case study, virtual reality has been used in project management meetings to facilitate communication and to support decision-making. We consider how the use of virtual reality actually influenced on group dynamics and make concluding remarks underpinning the use in a traditional meeting room environment.

We have used activity theory as a framework to begin method development for observing and analysing the effects of virtual reality on interaction and related work practices. The empirical findings point out, that new visualization instruments have effects on the 'division of labour'. Following five traditional meeting interaction characteristics showed changes at group dynamics. When virtual reality was used as a presentation tool, the interaction between participants became more balanced. Activation of all participants, most probably, leads to enhanced mutual understanding, and furthermore to better results in the whole project.

KEYWORDS: *Infrastructure construction, Virtual Reality, Meeting, Interaction, Decision making*

1. INTRODUCTION

Communication in large urban planning and infrastructure projects usually involve a great number of stakeholders, which is a special challenge. It can mean different things to dissimilar people in different situations, and may also have a variety of different meanings, contexts, forms and impacts (Dainty et all, 2006, p22). Major development projects usually take a long time to proceed, even up to 25 years or more (Porkka et al. 2012A). Many important decisions are made early, such as boundaries for upcoming costs, functionality, usability and relation to surroundings. Time is short to discuss in these subjects in early meetings. There are many stakeholders, who view the process from different perspectives, including professionals such as engineers, architects, and planners and non-specialists such as clients and users (Bouchlaghem, 2005). Communication capabilities of knowledgeable participants may also be intensified, when compared to stakeholders with narrow understanding. Sometimes there is also confusion with technical language and adversarial culture where companies value their interest, preventing straightforward information flow between stakeholders (Dainty et al., 2006, pg.2).

Transparent communication is a necessity for active stakeholder contribution. Many of the problems that develop in projects are a result of both the temporary and interdisciplinary nature of project teams (Dainty et all, 2006, pg.2). Hence, the choice of which tool is the most appropriate, depends upon, the nature of the information and recipient, and the desired outcome from the communication. (Dainty et al., 2006, pg.83). A traditional design communication is often built on a paper-based graphical representation, which consumes time and moderates

Citation: Porkka, J., Kähkönen, K., Kuula, T., & Rannisto, J. (2013). Virtual reality for meeting interaction in infrastructure construction projects. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

teamwork (Porkka, 2012B). Currently model-based applications are being increasingly utilized at planning phase. Virtual reality (VR) offers a promise for design visualisation to convey messages without communication difficulties (Reich et al., 1996). From a variety of tools available for communication, visualisation is the easiest common language, where professionals and non-specialists are able to relate and understand the content of design proposals (Porkka et all, 2012B).

The benefits of visualisation in group context have not been thoroughly addressed. Use cases have illustrated the benefits of synchronous collaborative information visualisation, but very few empirical studies have rigorously examined the impact of visualization on group knowledge work (Bresciani and Eppler, 2009). Bresciani and Eppler (2009) reported visualization helping to achieve higher productivity, higher quality of outcome and greater knowledge gains. Moreover, visualization also helps to work more collaboratively and communicate ideas efficiently (Bouchlagshem et al., 2005).

Success during project execution depends increasingly on individual capabilities to work together. Challenges are often related to the unique and complex nature of projects. Visualization techniques can facilitate shared understanding across interdisciplinary groups, which is required between all of the parties involved in collaborative design methodologies (Bouchlaghem, 2005). Moreover, virtual reality has started to be included to participatory methodology (Mobach, 2008). Although the use of virtual models has its advantages, there are still multiple challenges that diminish their potential in project use. These challenges are at high level related to non-human or human topics. The non-human topics cover issues like deficient processes, practices and tools. The human-related topics include for example lack of communication and interaction between relevant stakeholders. Currently most virtual reality applications, for example, require manual work to generate virtual models. There is need for cost-efficient applications, connecting intelligently to planning process and modelled plans. If the virtual model is generated nearly automatically, virtual reality applications become very stimulating for everyday use. Interaction is a key element in current design practice due to the high number of disciplines involved in design formation and decision-making.

This paper focuses on the observations made in one particular project meeting partially utilising virtual reality in communication in an ongoing large infrastructure construction project in Finland. First, we set out the key theoretical principles for virtual reality applications and describe the methodological approach of activity theory used in observing the meeting interaction. Virtual reality was used to facilitate communication and to support decision-making. Later, we consider how the use of virtual reality actually influenced on group dynamics and make concluding remarks underpinning the use in a traditional meeting room environment.

2. INTERACTION IN MEETING AND ACTIVITY THEORY

Construction industry is highly knowledge and people intensive. The interaction tends to be characterised by unfamiliar groups of people coming together for short periods before disbanding to work on other endeavours (Dainty et all, 2006, page 22). It's complicated to combine individual project team members' diverse skills, expertise and knowledge efficiently in meetings. Therefore, work practices in design formation are shifting towards more cooperative approach. Collaborative and participatory design methodologies are more and more highlighted. The collaborative aims at improving cooperation between professionals, while the participatory methodology contributes to citizens and end-users. Nevertheless, the teams operate through a set of varied meetings in construction industry. Main types of typical project meetings can be classified as:

i) Industry professionals' meetings, i.e. master plan review meeting by the core design team.

ii) Non-expert meetings, i.e. public hearing events.

In this paper, we focus on interaction between industry professionals. Unfortunately, there is not just one way for researcher to collect and analyse conversational data from this kind of meetings. Researchers tend to make their own conceptual categories for conversational data. We decided to look for a generic framework, which enables us to analyse interactions in meaningful perspectives.

One potential theory in social sciences to investigate collective activity and interaction is activity theory. The roots of activity theory have its origin from Russian psychology, and in Scandinavia the attention has evolved from individuals towards community. The theory relies on the concept of expansive learning, where the learners construct a *new object* for their collective activity and implement this *new object* in practice (Engeström, 2010). We have utilised the activity system model as a theoretical framework for analysing the meetings. We examine a micro level concentration through individuals participating in the meetings and reflect perceived results back to whole project interaction at macro level.

The activity theory model is a general description of collective human activity with seven key elements linked together (Engeström, 1999). In the activity system model (University of Helsinki, 2012), the *subject* refers to an individual or a sub-group whose agency is chosen as the point of view in the analysis. The *object* refers to the 'problem space' at which the activity is directed and which is moulded and transformed into *outcomes* with the help of physical and symbolic, external and internal mediating *instruments*, including both tools and signs. The *community* comprises multiple individuals and/or sub-groups who share the same general object and who construct themselves as distinct from other communities. The *division of labour* refers to both the horizontal division of tasks between the members of the community and to the vertical division of power and status. Finally the *rules* refer to the explicit and implicit regulations, norms and conventions that constrain actions and interactions within the activity system.

Since the elements of activity are linked together, changes in one element affect the others. The changes may also cause contradictions between the elements. For example, what would happen when virtual reality as an ‘instrument’ is added into the system? In this paper, one particular meeting is seen as a case for observation and analysis. Thus, the meeting represents a ”micro activity system” with participants as ‘subjects’ and meeting goals as ‘objects’. However, the activity system perspective also reveals the more complex nature of the construction project and how meetings are bounded to the larger picture.

3. CASE STUDY

This paper builds on a case study, one meeting in a large infrastructure construction project in Finland, where virtual reality was used concurrently to traditional presentation methods in facilitating communication and to support decision-making. The client of the project is a governmental organization, who ordered the planning work from consultants and appointed experienced professionals to follow up the planning work. The team has prepared a general plan and is currently in process of developing a detailed plan. The detailed plan determines the accurate positions, identifies land allocations, and specifies traffic arrangements also to pedestrians and public transportation (The Finnish Transport Agency, 2010). However, this research aims at developing a method to observe meeting interaction and facilitates the developed method in one particular meeting situation. Once the method is tested and developed, the approach may become an integral part of procedural changes in organising project meetings.

3.1 Subject of Research

The subject of research was a regular project management meeting during the detailed plan preparation phase. The meeting was held between the client, appointed professionals and consultants, encompassing seven participants from which six were men and one was woman. The ages of seven participants varied between mid thirties to mid fifties. The management team was experienced and four out of seven members had lots of practical knowledge from similar projects. The rest were also skilled in their assigned tasks. This set up created an uncomplicated atmosphere for the project management meeting. The stakeholders appreciated each other, and communication was transparent and straightforward throughout the whole meeting.

The schedule of meeting was remarkably tight and agenda included plenty of topics. Since the project is large, the disciplines are progressing differently in various parts of the plan. The aim of the meeting was to share understanding and discuss issues that need instant attention. Altogether, the whole meeting lasted for four and half hours. In the beginning, the team browsed through the economical issues, and later, the research on observing interaction in actual planning topics started. The research consisted from seven topics. The three-hour section was held without breaks. The plan was developing and in one topic they had just started to collect ideas, while some others already had a preliminary plan.

The meeting was organised in a standard meeting room, which is presented in Figure 1 (Fig 1). Participants were seated on two-sides of a long table, and the whiteboard to project images was at the end of table. The consultant representatives led the meeting. Their two managers first introduced the topics. After the introduction a discussion period started and all participants had an opportunity to share their opinions. Consultants also had a project secretary, who showed the materials from beamer and distributed printed materials to stakeholders. The secretary wrote official meeting notes and operated various tools for modelling and virtual reality applications.

Fig. 1: Meeting room setup and two tools used in making decisions - a traditional map on the left and a virtual reality presentation at right (Photos courtesy of Janne Porkka).

Conversations in the meeting were observed by a group of four researchers. Before observing the interaction, researchers assumed that the use of virtual reality has positive influences on collaboration and further to assisting the decision-making. To complement observations, the whole meeting was recorded with sound and several photos were taken for documentation. The researchers took field notes and had an access to official project bank for shared materials and documents.

3.2 Applied Virtual Reality Application

Many key stakeholders have experienced difficulties in changing the current way of working towards model-based practices. Virtual reality has been found to offer promise for design visualisation to convey messages with reduced communication difficulties between different stakeholders. In other words, virtual reality lowers a threshold to interact. Unfortunately, virtual reality models usually require manual work upon creation from modelled plans. Since the plans are composed of numerous sub models, the effort of manual work done repeatedly might be too cumbersome for everyday production. There is a need for cost-efficient off-the-shelf applications connected directly to these plans. Then, virtual reality applications become more usable for municipalities and developers.

Vianova's Novapoint Virtual Map (Vianova, 2013) has been applied in the case study. Multi-disciplinary and complex design data in standard data exchange format is semi-automatically converted with parametric rules into a virtual reality presentation. Multiple sub models are converted into the same presentation, and dynamic linkage keeps track on updates to combined model. User has many options for viewing data and design alternatives can be selected by managing layer visibility. Presentation reveals conflicts like two objects colliding, one object hiding another and faults in geometries. However, these are model-based issues that can be easily corrected.

The application has useful functions for meeting context. There are multiple navigation modes like driving and flying. For meetings the easiest navigation mode is pre-stored camera viewpoint and path. The conflicts can be stored as viewpoints with a comment, and request for change goes back to planners. Activities in Virtual Map may be recorded to images and video. The sharing of model is enabled to separate free viewer or web page.

4. RESULTS AND OBSERVATIONS FROM THE MEETING

This research aims at developing a method to observe interaction in a meeting context. The participants studied in project management meeting were consultants, experts and client, who altogether established the community interacting on objects. The studied objects were seven topics in the meeting agenda (see details in a Table 1). The division of labour included first the introduction of a topic by a consultant and then the object was open for discussion between participants. Therefore, each participant had an opportunity to pose comments, and in fact, these comments led to valuable considerations while all stakeholders interacted. When the discussion of topic reached an end, the consultants together with the client made the closing remarks on how the plan is developed further.

As presented in table 1, topics were presented with the help of various tools. The first and second topic included status and schedule presented by tables, text documents and bar charts. Both of these topics did not gain added value from leveraging virtual reality in communication. However, the discussion with participants revealed that the added value comes when plans are accurate. Virtual reality was used in topics three and seven for design review and alternative comparison facilitated by maps, general plan, virtual reality visualization, alternative virtual reality visualization and section plans. Remaining three topics, numbered as four, five and six, were communicated with conventional tools like maps, text document, table, images and section plans in order to review designs. The partial use of virtual reality in communication enabled researchers to compare and contrast their impacts to conventional tools.

Table 1: General data and perceived results of observing seven topics in the project management meeting.

			Perceived communication (%)		Perceived comments (%)		
	Goal of topic	Tools used	Introduction	Discussion	Consultants	Client	Experts
Topic 1	*Status*	*Table, text documents*	83	17	38	25	38
Topic 2	*Schedule*	*Bar chart*	43	57	50	42	8
Topic 3	***Design review***	***Maps, General plan VR visualization***	**17**	**83**	**47**	**31**	**22**
Topic 4	*Design review, Idea generation*	*Maps, text documents*	56	44	50	25	25
Topic 5	*Design review*	*Maps, table, images*	48	52	57	24	19
Topic 6	*Design review*	*Table, section plans*	81	19	67	25	8
Topic 7	***Alternative comparison***	***Alternative plan VR visualization, section plans***	**29**	**71**	**40**	**27**	**33**

We observed how much time was spent on to communicate each topic and noticed significant time differences in communication. The perceived time difference, as presented in Figure 2, fluctuated from ten minutes to nearly an hour. The more the time was, the wider the topic appeared to be in terms of details or planned content. Within each topic, the dialogue was verified from video and researchers split the conversation into consultant's introduction and discussion section. As an average, the percentage for introduction was 46% while discussions took 54% of the time. Interestingly, the share of introduction was significantly smaller in topics that utilised virtual reality, respectively 17% and 29% in tasks three and seven. On the other hand, the tasks with conventional tools seem to consume more time to be explained, as presented in Table 1 and Figure 3.

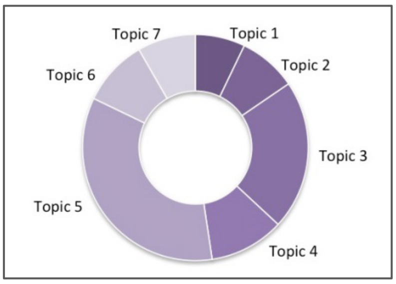


Fig. 2: Perceived length of seven topics in agenda as percentages from the whole meeting.

All representatives participated to conversations. Clients' project manager was very experienced and interested to discuss, which led to an active role throughout the project management meeting. Within the discussions, the client had a strong linkage to appointed experienced professionals. Two of the experts were experienced with model based planning, and in fact, one of the aims in the whole project is to utilise model-based applications more efficiently in the planning process where virtual reality is applied to enhance communication.

The amount of comments participants made during communication is actually a reliable indicator for participation. The tracking emphasised how participants are participating. Moreover, instead of calculating every comment we focused on how many first comments the participants made to bring up a new subject to discuss (see participants comments on right-hand side in Fig 3). When consultant started topic introduction we added one comment. When the introduction ended and participants started to bring new subjects to discussion, the calculation continued. For example, when someone posed a question: "what is the distance between the columns?" the resulting conversation was marked for the same participant because it provided the direction. Our approach promotes the activeness of participants. However, we want to remind that the results are based on the findings of one meeting. Thus, broader generalisations on how the use of virtual reality effect to interaction and meeting dynamics are preliminary. The sample of several meetings is needed to confirm the findings.

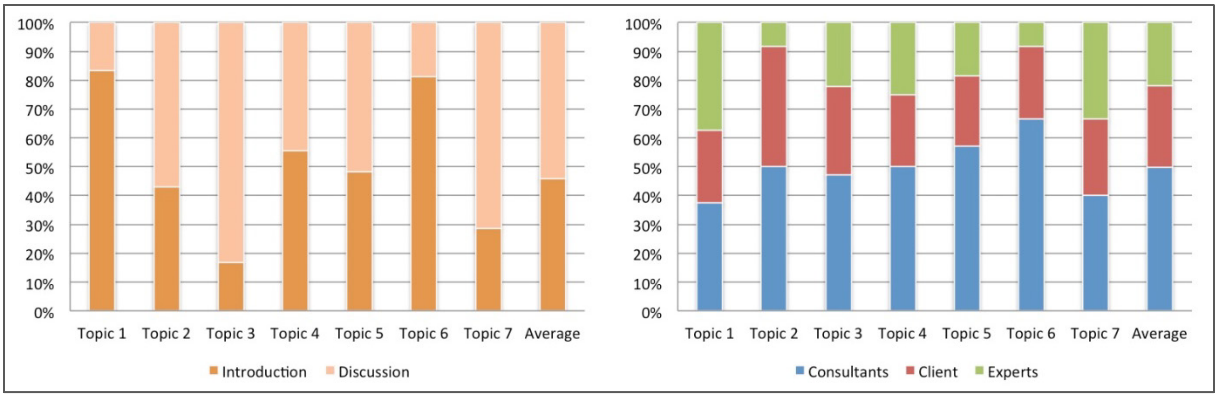


Fig. 3: Graphs from perceived communication times (left) and perceived participant comments (right).

Some participants, especially client and experts, appreciated the use of virtual reality in interaction. Throughout the conversations, participants often reflected plans to resident opinions and comments from regional businesses, to support detailed discussions. Virtual models in meeting were shown by the project secretary who did not contribute to other topics, and thus it appears that technology has an impact on the division of labour.

5. DISCUSSION

Project management meeting provides great perspective on how plan evolves constantly from meeting to meeting. The outcomes of this meeting are about to become objects for the following meeting. The use of model-based applications in early planning has been stated to provide coordination benefits (Porkka et al., 2012B). For this research a virtual reality solution enabling semi-automatic virtual model generation from modelled plans was used. The data from live meeting context gave us better understanding on the characteristics of virtual reality in interaction. Although the subject of research was not scientifically rigorous due to small sample, it clearly demonstrates how an active participation is essential for successfully reaching the meeting objectives.

Virtual applications have an additional value in introducing plan to participants. Compared to the traditional tools, such as text documents, tables and images, the introduction seemed to be quicker with the help of virtual reality. This is demonstrated in Figure 4, where it is obvious, that the content of the topic has a lot of effect on the discussion time. The goal of the topic four was to generate ideas. However, much time was spent to introduce the object. Altogether, it seemed that it was easier for participants to understand content more quickly when virtual model was used and more emphasis was paid on problem solving. Relations between discussions and introductions varied in a ratio from 0.2 to 5. When topic leveraged virtual reality the ratio was higher (2.5-5), meaning that there was over two times more discussion about the details of plan when compared to the traditional tools in introducing the plan. In other words, if there is certain time reserved to review a plan and introduction time is shorter, there is relatively more time to interact and discuss about the solutions for further development.

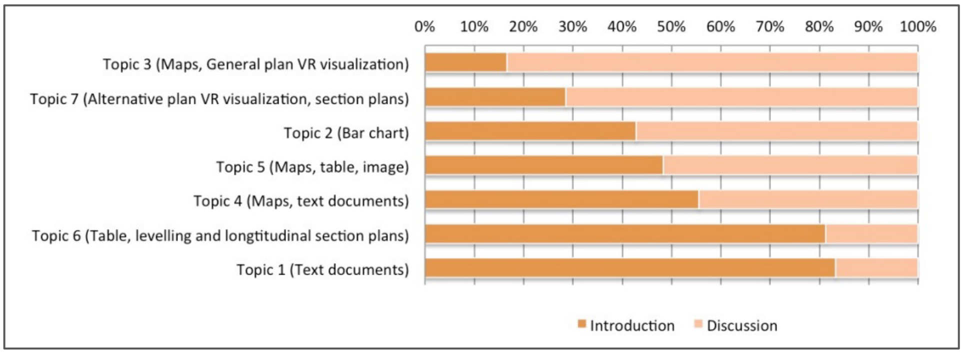


Fig. 4: Perceived topic communication (introduction and discussion) and tools.

We also noticed that virtual model helps to share understanding between the participants of various backgrounds. Thus, bringing virtual model as a new 'instrument' into the activity system seems to change the division of labour towards more democratic and even way to discuss. The degree of participation (see Fig. 5) reveals that consultants had a primary and leading role in the meeting. When virtual reality was used, the nature of the conversations changed and an increased participation of client and experts were noticed. As a resultant to that, the activity of consultants decreased. Therefore, it is also reasonable to consider that use of virtual models may shift the roles of participants towards activating more technically competitive younger generation.

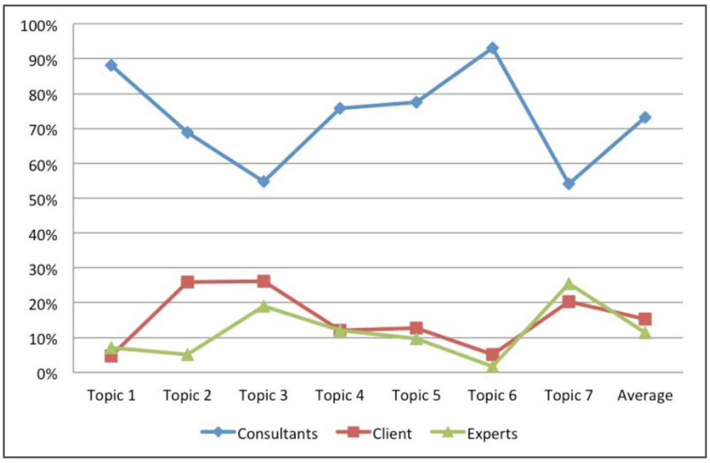


Fig. 5: Degree of participation during meeting (%).

6. CONCLUSION

This paper has presented observations from the project management meeting on understanding better, how virtual reality influences on meeting interaction. We have used the activity theory viewpoint as a framework to begin method development for observing and analysing the interaction and related work practices. In a nutshell, the developed method monitors following meeting characteristics: perceived communication time per topic, perceived communication time inside the topic (split to introduction and actual discussion), perceived amount of participant comments, perceived amount of first comments to bring new subject into the discussion, and degree of participation.

Active participation is essential for successfully reaching the meeting and project objectives as a whole. The empirical findings collected through observations and recordings indicate that bringing new technologies into a sensitive meeting situation must be facilitated carefully. Large projection-based immersive environments have potential to enhance collaboration and exchange of ideas (Simon and Scholz, 2005). Based on our findings from the traditional meeting room environment, new visualization instruments have effects on the 'division of labour' during the meeting. When virtual reality was used as a presentation tool, the interaction between participants became more balanced. This interesting group dynamics shift was supported by a remark that virtual applications have additional value in introducing the plan to other stakeholders. There was over two times more detailed, beneficial discussion in comparison to using traditional communication tools. Balancing the degree of participation between participants, most probably, leads to enhanced mutual understanding, and furthermore to better results in the whole project. When there is a certain time reserved for plan review, virtual reality leads to better opportunities for developing the plan. Besides, it is also reasonable to consider that roles of generations are shifting towards the activation of younger people.

Efficient use of virtual reality requires procedural changes in organising project meetings. We recognised a contradiction between the 'subjects' and the 'rules'. Sometimes, the chairperson was unable to control time used in communicating one topic and allocated time for next topic diminished. Based on the activity theory, the more in balance without contradictions different activity system elements are, the better the interaction will be. However, it should be pointed out that activity theory alone is not sufficient for evaluating new meeting practices' impact on the whole construction project, thus supporting methods are needed. The impacts of decisions on design practices need more emphasis. The method presented and tested in this paper is a good starting point. People should be open to new ways of working and willing to take collaboration and participation methodologies into work practices. We will together, with case stakeholders, focus in the future for developing a new responsive design practice.

7. ACKNOWLEDGEMENTS

This research has been supported by the Finnish Funding Agency for Technology and Innovation (TEKES) under the project 'VIREsmart'. Authors are grateful for the team enthusiasts at Finnish Traffic Agency, Centre for Economic Development, Transport and the Environment, City of Espoo, Sito Ltd., Vianova Systems Finland Ltd., and Ramboll Finland Ltd. Main author of the paper, Mr. Janne Porkka, is a doctoral candidate in the Faculty of Built Environment at Tampere University of Technology. Special thanks for VTT colleagues, Mr. Juha Hyvärinen, Mrs. Mirkka Rekola, and Ms. Nusrat Jung, for support and constructive comments to develop content in paper.

8. REFERENCES

Bouchlaghem, D., Shang, H., Whyte, J. And Ganah, A. (2005). Visualisation in architecture, engineering and construction (AEC), *Automation in construction,* Vol. 14, Iss. 3. pp. 287-295.

Bresciani, S. And Eppler, M. (2009). Evidence from an experimental evaluation, *Visualization and Computer Graphics*, Vol. 15, Iss. 6. pp. 1073-80.

Dainty, A., Moore, D. and Murray, M. (2006). *Communication in Construction, Theory and Practice*, Routledge.

Engeström, Y. (1999). Innovative learning in work teams: analysing cycles of knowledge creation in practice, in: Engeström, Y. et al (Eds.) *Perspectives on Activity Theory*. Cambridge University Press, Cambridge. pp. 377-406.

Engeström, Y. (2010). Activity Theory and Learning at Work, In Malloch, M. et all (Eds.) *The SAGE Handbook of Workplace Learning*, Sage publication Ltd. pp. 74-89.

Mobach, M. P. (2008). Do virtual worlds create better real worlds? *Virtual Reality journal*, Vol. 12, Iss. 3, 163–79.

Porkka, J., Jung, N., Jäväjä, P., Suwal, S., Savisalo, A., Päivänen, J. and Sireeni, J. (2012/B). Increased interaction with multi-user virtual reality in construction projects, in Lin Y-C. & Kan S-C. (eds.) *12th International Conference on Construction Application of Virtual Reality - ConVR 2012*. Taipei, Taiwan, November 1-2. pp. 434-42.

Porkka, J., Jung, N., Päivänen, J., Jäväjä, P. and Suwal, S. (2012/A). Role of social media in the development of land use and building projects". In Gudnason G. & Scherer R. (eds.) "eWork and eBusiness in Architecture, Engineering and Construction, ECPPM 2012". Reykjavik, Island, Jul 25-27. pp.847-54.

Reich, Y., Konda, S.L., Levy, S.N., Monarch, I.A. and Subrahmanian, E. (1996). Varieties and issues of participation and design, Design Studies, Vol. 17, No. 2, 165–180.

Simon, A., and Scholz, S. (2005). Multi-viewpoint images for multi-user interaction, *Proceedings of Virtual Reality'05*, IEEE, Germany, Bonn, March 12-16th, 7pg.

The Finnish Transport Agency (2010). *Road planning phases (In Finnish)*, electronic publication from The Finnish Traffic Agency and Centre for Economic Development, Transport and the Environment. 20 pg.

University of Helsinki (2013). Structure and description of activity system. Available online at: http://www.helsinki.fi/cradle/activitysystem.htm (Accessed 22.5.2013)

Vianova (2013). Novapoint Virtual Map product sheet. Available online at: http://www.vianovasystems.com/Products/Novapoint-products/Novapoint-Virtual-Map#.UX2ZTpV21v0 (accessed 22.5.2013)

IMAGE-BASED LOCALIZATION FOR AN INDOOR VR/AR CONSTRUCTION TRAINING SYSTEM

Ludovico Carozza, Frédéric Bosché & Mohamed Abdel-Wahab
School of the Built Environment, Heriot-Watt University, Edinburgh, UK

ABSTRACT: *Virtual /Augmented Reality (VR/AR) technologies have been increasingly used in recent years to support different areas of the construction industry. Their simulation capabilities can enable different construction stakeholders to evaluate the impact of their choices not only on the built environment, but also with regard to the correct execution of operational procedures. Training providers, such as Further Education (FE) colleges, can also enhance their trainee's experience through the simulation of realistic construction contexts whilst eliminating health and safety risks. Current approaches for the simulation of learning environments in Construction, such as Virtual Learning Environment (VLEs), provide limited degree of interactivity during the execution of real working tasks. Whilst immersive approaches (e.g. CAVE-based) can provide enhanced visualization of simulated environments, they require complex and expensive set-up with limited practical interaction in real construction projects context.*
This paper outlines a localization approach employed in the development of an Immersive Environment (IE) for Construction training, cheaper than CAVE-based approaches and which has the potential to be rolled-out to the FE sector for maximizing the benefit to the construction industry. Pose estimation of the trainee is achieved by processing images acquired by a monocular camera integral with his head while performing tasks in a virtual construction environment. Realistic perception of the working environment and its potentially hazardous conditions can thus be consistently delivered to the trainee through immersive display devices (e.g. goggles).
Preliminary performance of the localization approach is reported in the context of working at heights (which has a wide applicability to a range of construction trades, such as scaffolders and roofers), whilst highlighting the potential benefits for trainees. Current limitations of the localization approach are also discussed suggesting directions for future development.

KEYWORDS: *Image-based, localization, VR/AR, and construction training*

1. INTRODUCTION

Applications of Virtual/Augmented Reality (VR/AR) to the Architecture, Engineering and Construction (AEC) sector have been gaining considerable attention from the industrial and academic community for their inherent simulation capabilities in different contexts, such as: enhanced project visualization and design review (particularly with BIM) (Bosché et al. 2012, Bassanino 2010, Woodward et al. 2010), on-site information retrieval (Yeh et al. 2012), and plant operatives training (Wang et al. 2004). However, construction trades (such as scaffolders, roofers, painter and decorators, etc.) have not yet benefited from training in simulated work environments by using VR/AR technology. The key benefit of using VR/AR for construction trades training is that it can create a realistic learning environment for training, e.g. working at height, without exposing trainees or instructors to any health and safety risks (Abdel-Wahab, 2012). It can provide immediate interaction with realistic environments, through real-time feedback to ensure that trainees consistently perform to the required standards.

VR systems currently considered in construction education and training are essentially based on Virtual Learning Environments (VLEs), like Moodle and Blackboard (Abdel-Wahab, 2012), or CAVE-type 3D immersive environments. Simulated environments are developed for VLEs that are essentially educational video games with totally simulated environment that the trainee interacts (and learns) with. This type of virtual training results in a limited degree of interactivity and immersion, two aspects deemed of great importance in the construction sector context (Abdel-Wahab 2012, Dalgarno et al. 2010).

On the contrary, immersive learning environments can provide potential learning benefits such as: immersive spatial representation, by providing enhanced visualization of the virtual environment through 3D immersive displays; and immediate interaction with realistic environments, through a direct and immediate feedback

Citation: Carozza, L., Bosché, F. & Abdel-Wahab, M. (2013). Image-based localization for an indoor VR/AR construction training system. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

reflecting consistently the actions performed by the trainee (e.g. trainee's movements). These enhanced functionalities can find application in realistic training in operational procedures, e.g. construction equipment operation (Wang et al. 2004), and safe simulation of hazardous conditions, e.g. working at heights.

3D immersive environments currently investigated and used for construction training are mainly CAVE-type environments (CruzNeira et al. 1992; Lau et al. 2007). These require the set-up of dedicated facilities with significant impact on complexity and costs. These facilities include, among others, the installation of entire plant simulators with dedicated hardware for interaction, or the set-up of huge video screens and dedicated projectors, with impact on installation costs and energy consumption. ACT-UK (ACT 2009) is an example of CAVE-type environment that was developed for construction management training (deVries et al. 2004).

The work presented here is conducted in the context of the Immersive Controlled Environment (ICE) project, which aims at simulating a real construction workplace for real construction activities conducted by the trainee without any risk of injury (immersive experience), as well as assessing the trainee's performance (controlled experience). As part of this project, an alternative 3D immersive environment is presented that leverages significant advancements recently made in localization and visualization technologies, in particular: portable immersive display, and image-based localization systems.

Novel portable immersive display systems, such as (Vuzix), offer the immersive functionality of CAVE-type systems for a fraction of the cost. Our system is based on the use of such display systems. However, the disadvantage of such systems is that they require robust approaches for tracking the movement of the head of the user. This localization functionality plays a key role in providing the trainee with a consistent and realistic spatial perception of the simulated virtual scenario.

Several techniques can be considered to resolve this localization problem, and we propose to use an image-based approach applied on a video sequence acquired from a monocular camera integral with the trainee's head (i.e. with the display goggles). The acquired images are registered with respect to a three-dimensional visual model of the training room, acquired in advance once and for all. The trainee's head pose is then employed to deliver any virtual construction environment in a consistent manner through the display goggles. Compared to other localization approaches, image-based approaches offer significant advantages in terms of set-up complexity and cost. As a result, the overall system that we propose has the potential to deliver highly immersive, consistent and realistic VR/AR experiences at a fraction of the cost of CAVE-type systems.

This paper focuses on the head localization functional component. The proposed approach is described and its performance assessed in terms of accuracy, robustness and processing time. This assessment ultimately determines what the future of the proposed approach can be with regard to VR/AR systems.

This paper is structured as follows. In Sect. 2, current technologies proposed for localization are briefly reviewed, highlighting advantages and drawbacks of different approaches. In Sect.3, we describe our localization approach in the context of the ICE project, emphasizing the strategies devised to cope with the most important localization issues. The experimental assessment of the performance of our approach is presented and discussed in Sect. 4. Benefits and limitations of our approach are discussed in Sect.5, along with directions for future improvements.

2. BACKGROUND

Accurate and robust localization (i.e. estimation of position and orientation) of the viewpoint within the environment is crucial to provide consistent interaction with the user. Mainly two general approaches are applied to localize and track objects (head of the user, reference points of a tool, etc.) within its environment: inside-out (ego-motion or direct) and outside-in (indirect) approaches. According to these approaches, information provided by different sensors mounted internally or externally, respectively, to the entity to be tracked is processed. Global and local position systems (GPS, WIFI), environment sensors (RFID), as well as Inertial Measurement Systems and vision-based systems, constitute the main state-of-the-art technologies employed to this purpose (Feng Zhou et al. 2008). Integration of different technologies (acoustic, magnetic, inertial, optical, etc.) within hybrid approaches has also been proposed to cope with the drawbacks of single approaches by exploiting complementary performances (Feng Zhou et al. 2008, Ligorio and Sabatini 2013). Desirable features of 6-DOF localization methods include, among others, coverage and range limitation, robustness to environment interferences (magnetic, visual occlusions, etc.), robustness to fast motion dynamics, and absence of drift for long range paths.

In the context of CAVE training approaches, hybrid systems are usually employed. Inertial-ultrasonic hybrid tracking (Intersense 2002), as well as multi-camera tracking of optical fiducial markers tracking, based on LED (Welch. et al. 2001) or reflective beacons (Pintaric and Kauffmann 2007) are currently among the solutions employed. These systems require on-purpose set-up and calibration to achieve accurate localization – at the expense of several thousand dollars.

Vision-based approaches are nowadays standing out due to low cost and widespread availability of digital cameras. Broadly speaking, issues in terms of robustness to motion patterns (abrupt scale and view-point changes, lighting conditions, blurring, etc.) and time responsiveness (i.e. latency) still have a significant impact, so that requirements in computational resources and scalability to large environments are in general of crucial importance (Dong et al. 2009). Moreover, important issues concern relocalization after tracking failures and error drift, especially for closed loop sequences. State of the art vision-based methods are based on global localization approaches (Skrypnyk and Lowe 2004) that conceptually overcome these issues, but often at the expense of a greater computational burden. The works in (Lim et al. 2012, Dong et al. 2009) rely on the a-priori visual knowledge of a three-dimensional model to establish 2D-3D correspondences between the image domain and a three-dimensional reference frame. For each processed frame, camera/space resectioning algorithms (Hartley and Zisserman 2003) are employed to determine from these correspondences the absolute 6-DOF pose of the camera in the three-dimensional reference frame. Generally, for computational reasons, matching of sparse visual descriptors, rather than recognition of geometric structure (e.g. lines/shapes) is employed concurrently with other strategies, like space partitioning (Tingdahl et al. 2012, Carozza et al. 2012) and keyframe selection (Dong et al. 2009) to prune the search space and speed up the process.

3. OVERVIEW OF THE PROPOSED SYSTEM

We propose a vision-based head localization approach that is motivated by the works of Carozza et al. (2012), and Lim et al. (2012), employing the a-priori visual knowledge of a three-dimensional model to establish 2D-3D correspondences between the image domain and a three-dimensional reference frame. The training immersive environment we devised consists of a training room, conveniently covered with textured images, for example with posters (Fig. 1).

Fig. 1: Panoramic image of the training room whose walls have been conveniently covered with textured pictures.

In an off-line process, pictures of the room are acquired and processed in a 3D reconstruction pipeline, resulting in a 3D map of visual features (that are mainly extracted from the textured images). It is important to note that our approach does not require the on-purpose setup of fiducial markers with specific configuration (e.g., known spatial distribution, visual pattern, markers' optical reflectivity, etc.), which can be complex and time-consuming, nor does it require the calibration of multiple cameras. Instead, the physical boundary of the immersive room simply needs to be covered with randomly positioned textured images that just need to be at an appreciable scale with respect to the camera field of view and the room size.

During on-line operations, the trainee is equipped with a monocular camera, integral with his head, i.e. with the immersive display goggles. In our system, the camera points towards the rear or side to reduce occlusion issues, and captures images of the room boundaries in real-time. For each image, visual features are extracted and matched against those contained in the map of 3D features created offline. The resulting matches enable the calculation of the position of the camera, and subsequently of the trainee's head. The estimated head pose is employed to render in the VR goggles carried by the trainee the corresponding view of the construction virtual environment experienced.

The off-line process for reconstructing the three-dimensional map of visual features of the room is described in Section 3.1. Then, the on-line process for localizing the head of the trainee/user within the room is described in Section 3.2.

3.1 Off-Line Reconstruction Stage

This stage aims at creating a 3D model of the visual features of the training room, whose boundary has been covered with pictures (see Fig. 1). For this, a set of overlapping pictures of the training room is acquired from different viewpoints. We call this set of pictures the reconstruction set. We then perform the 3D reconstruction of the SIFT (Lowe 2004) features, extracted from the reconstruction set of pictures, through sparse bundle adjustment – we use the Structure-from-Motion Bundler framework (Bundler 2006) described in (Snavely et al. 2007). As a result, 3D coordinates of SIFT features, as well as estimations of the camera intrinsic (focal length and distortion coefficients for a pin-hole camera model) and extrinsic (i.e., position and orientation) parameters are achieved (for more details, see Bundler 2006). The resulting 3D point cloud is filtered using a thresholding minimum number of cameras contributing to the reconstruction of each point, num_count, in order to select only the "best reconstructed" reference points.

SIFT are currently considered as the best visual descriptors in terms of robustness (Gauglitz et al. 2011), but at the expense of a considerable computational effort for matching pairs of features. This seriously limits image processing speeds, and subsequently in our case VR quality performance during on-line operations. Following an approach similar to the one adopted by Lim et al. (2012), we exploit the achieved SIFT reconstruction, which has already reconstructed robust salient features, to compute more efficient descriptors for the corresponding 3D cloud. The following process is used: For each reconstruction image, SURF keypoints (Bay et al. 2008) are extracted. Then, the reconstructed camera pose is exploited to compute the 2D re-projections of the 3D points on the reconstruction image. Finally, for each SURF keypoint, the 3D point with the closest re-projection (within a search radius distance_threshold) is associated to the corresponding SURF descriptor, thus obtaining a database of 3D referenced SURF descriptors, hereinafter called map. This database is filtered again according to a minimum number of reconstructing cameras (this threshold being set to num_count/3), so that features with low repeatability are discarded. We note that all SURF descriptors matched to a given 3D point should be close in the descriptors' vector space, that is with distances (Euclidean, in the case of SURF) having a low-mean and low-variance distribution. This aspect has been investigated at a preliminary level, with our experiments showing mean distance values in the range of [0.18; 1.12] and distance variances in the range [0.01; 0.93]. Therefore, we propose to keep for a 3D point a unique descriptor with associated global feature strength as repeatability score, calculated by averaging the corresponding descriptors and their strengths respectively. This strategy aims at reduce the size of the database while preserving repeatable and distinctive features for better on-line performance.

3.2 On-Line Localization Stage

During on-line operations, i.e. in our context during a construction training session, the system processes the image sequence acquired live and in real-time from a camera mounted integral to the trainee's head (i.e. to the display goggles). We call this new set of camera images the target sequence. Different strategies are employed to estimate the pose of the camera from correspondences between the visual features extracted from each target image and the map created off-line. These are described below.

3.2.1 Initialization

When the first frame is processed, or the pose is completely lost, there is no clue about the camera pose, which hence needs to be initialized. SURF features are extracted from the processed target image and their descriptors matched with the N strongest SURF descriptors of the map (N=500, in our tests), organized in a k-d tree indexing structure (Skrypnyk and Lowe 2004) to improve efficiency. For this, efficient approximate nearest neighbor interrogation of the map is employed, followed by a ratio test (α=0.65) to prune false matching. This process ultimately retrieves, for each 2D keypoint extracted from the target image, the 3D coordinates of the "best" matching point in the map, leading to a set S(x2d, X3d) of one-to-one matching coordinates. The pose of the camera, that is the rotation matrix R and the camera centre position C, is then robustly determined employing RANSAC filtering followed by Levenberg-Marquardt optimization over the resulting set of inliers (Hartley and Zissermann 2003). To this purpose, the re-projection error is employed as cost function (see Snavely et al. 2007 Appendix 1 for more details), with the camera intrinsic parameters known from the off-line stage or other camera calibration methods (Bouguet 2004).

If less than min_num_inliers inliers are found, the pose is rejected, the corresponding frame skipped and the system remains in Initialization mode for processing the following target image. On the other hand, if the pose estimation is successful, the system switches to Tracking mode.

3.2.2 Tracking

Once the pose has been initialized successfully, for the subsequent frames the pose is estimated from 2D-3D correspondences achieved by performing feature tracking between consecutive frames. More in detail, given the set x2d(t-1) of image locations of the matched SURF features for the last successfully computed frame at time (t-1), the Lucas-Kanade-Tomasi tracker (LKT, Lucas et al. 1994) is employed to estimate their locations for the current image at time t, x2d(t). In general, tracking approaches permit to significantly speed up the 2D-3D matching stage by exploiting spatio-temporal continuity, so that local motion fields, sufficiently small for consecutive frame, can be quickly estimated from local image analysis. On the other hand, in the presence of large camera displacements due to abrupt motions, Relocalization is required to recover from lost poses. To identify such situation and perform relocalization, the same strategy as above could be applied: if less than min_num_inliers inliers are found, the Tracking is considered unsuccessful and the method re-enters the Initialization (i.e. relocalization) stage, so that the tracker can be reinitialized with new features to track for the subsequent frames.

However, Initialization is a time-expensive matching process that should be employed as little as possible. Therefore, a more robust tracking strategy has been put in place that reduces potential frequency of Initialization. In order to track a sufficient number of features, otherwise often lost after few frames, and also to prevent potential ambiguity in estimating pose due to uneven distribution of the tracked features, a measure of skewness for the spatial distribution within the image plane is evaluated at each frame. A lattice of T=16 cells is built on the current image and an occupancy map is computed with each cell assigned a score calculated as the number of keypoints located within it over a maximum number of features to track, F (we use F=160). As a measure of skewness of the scores' distribution, the Cyhelský's skewness coefficient is considered:

$$S = (C\_L - C\_R)/T$$

where C_L and C_R are the number of scores below and above the expected score (for a uniform distribution) 1/T.

If S exceeds the threshold S_TH (set to 0.65, in our tests), tracker resetting (Reset mode) is triggered for the subsequent frame, that is new features are added to the feature tracker by re-projecting on the 2D image plane the 3D features contained in the frustum of the previous successfully computed pose. In addition, local non-maxima suppression of the re-projected keypoints is performed in order to retain widespread strong features. In this way, a higher number of features with a more widespread spatial distribution can be tracked, with benefits in terms of less frequent relocalizations (Initialization or Reset mode) and robustness of the estimated pose. In fact, this tracking strategy can be even more robust with respect to the matching strategy, for example in presence of global illumination changes or blurring artifacts in less textured areas (presenting few weaker features to match). Tracking strategies are inherently prone to drift, and this strategy has also the aim of curbing this effect by performing periodic adjustment triggered by "poor quality" (i.e. poor feature distribution) of pose estimation.

In addition, in order to smooth the resulting camera trajectories, the computed poses are filtered using Extended Kalman filtering. The filter is initialized in the Initialization state and the pose is tracked accordingly while the system is in Tracking mode. The dynamic model adopted in this work is similar to the one described in (Davison et al 2007, Tingdahl et al. 2012), due to its trade-off between simplicity (only linear and angular velocities are modeled) and smoothing performance. To improve the numerical stability of the resulting dynamic system, preconditioning with a scaling factor λ=10 is applied to the 3D coordinates of the matched points of the map (i.e. the measures vector of the EKF), so to avoid that small values could lead to filter divergence (Perea et al. 2007). EKF results are rejected as unreliable if the changes in orientation are too severe or the residuals increase, indicating possible divergence, in which case *Initialization* is conducted.

4. EXPERIMENTAL RESULTS

In this section we present the results of several experiments. In particular, we focus on the performance of the localization approach for on-line sequences acquired for two different training rooms, for which both the room set-up as well as the motion patterns are different. The walls of the two rectangular rooms (ROOM1, and ROOM2, hereinafter) have been previously covered with textured posters with different pattern and size (see Fig. 1 for ROOM2), with different spatial arrangement for the two rooms, so to cover almost all the room perimeter and guarantee visual distinctiveness in the different parts of the room.

Both off-line reconstruction and on-line localization stages have been performed using sequences of images from videos of the rooms acquired by a hand-held digital camera (Panasonic CCD DMC-TZ6, 640 x 480, 30 fps MJPEG). The intrinsic camera parameters estimated by the Bundler framework during the off-line reconstruction stage are also used in the on-line experiments, which simulates the trainee's movements according to different motion patterns.

Moreover, a virtual model (a scaffold new a brick wall, in our example) was aligned manually with the room maps after the reconstruction stage, so that it can be rendered during the on-line stage according to the estimated camera pose for each of the processed video frames.

Tests were performed off-line on the video sequences on a Dell Aurora Alienware PC (Intel i7-3280 @ 3.6GHz, 8GB RAM). Videos with results are available at http://www.ice.hw.ac.uk/. To assess the performance of our approach, visual evaluation of the rendered views under the motion patterns has been performed initially to assess qualitatively the robustness of our approach. Furthermore, the reprojection error has been used as measure of accuracy. Time performance of the localization process has also been considered in view of addressing future latency issues that can potentially affect user experience.

4.1.1 Experiments in ROOM1

For the off-line reconstruction stages 265 video frames of the room acquired from different viewpoints have been used, yielding a map of 1348 SURF features. For the on-line stage, a video sequence of 1149 frames (duration 38 s) has been acquired moving around the room following a smooth motion pattern, still presenting compression artifacts and changes in scales. In Fig. 2 the mean reprojection error and the processing time for each frame are reported.

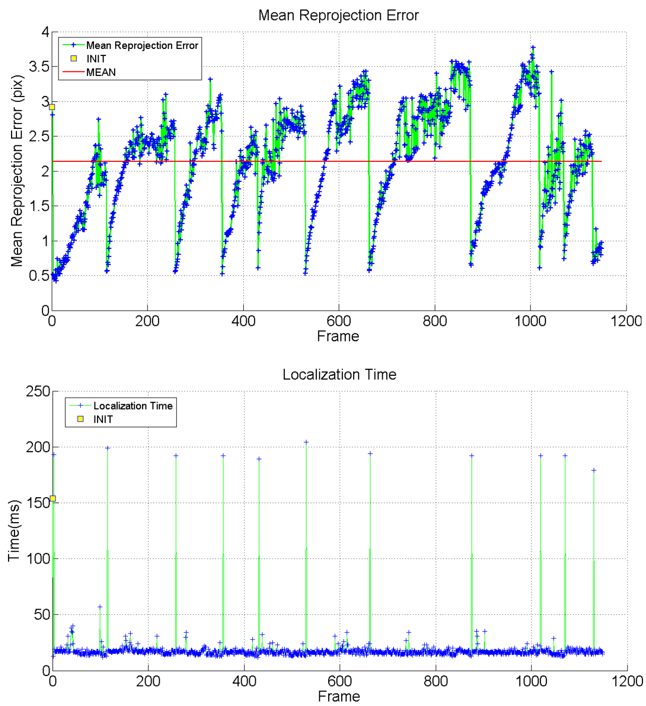
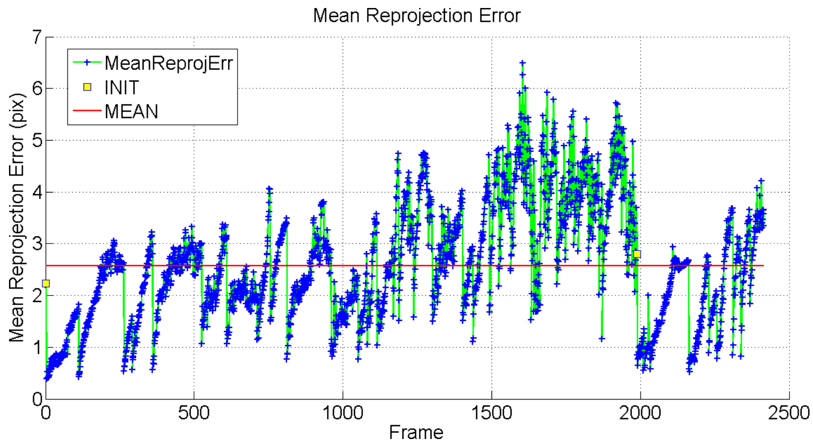


Fig. 2: Mean reprojection error (top) and processing time (bottom) for the localization stage for test in ROOM1.

As it can be noticed, tracking introduces some drift effect, adjusted periodically by the tracker reinitialization (*Reset* mode). The magnitude of the tracking errors (about 2 pixels on the average) is comparable with the ones obtained by other vision-based Virtual Reality applications (Klein and Drummond 2003). Visual estimation shows consistent views of the virtual environment for all the frames, with near real-time performance (25-30 fps) and some latency introduced by the occurrences of the more time-expensive Reset mode. It must be noticed that this is mainly due to a current inefficient implementation of this stage, that can be improved by taking advantage of space partitioning techniques (see Sect. 5).

4.1.2 Experiments in ROOM2

A map of 2266 features has been achieved from 153 video frames of ROOM2 through the off-line reconstruction stage. Results related with a video of 2415 frames (1.20 min) are shown in Fig. 3.



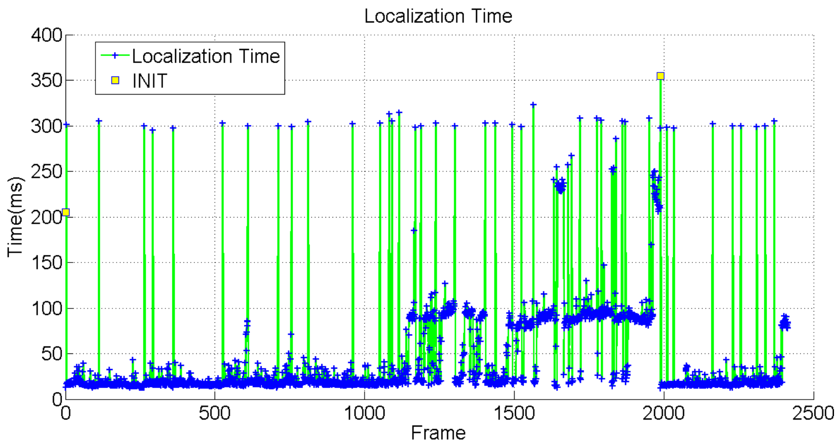


Fig. 3: Mean reprojection error (top) and processing time for the localization stage (bottom) for test in ROOM2.

Performance is comparable with the one obtained for the test in ROOM1 for almost all the video sequence. We note though that frames 1500 to 1718 rely on a low textured area (the room's ceiling) for which poor reconstruction was obtained (due to very few posters installed). In this case, the tracking strategy presents a drift that is then followed by the Initialization at frame 1988. A more efficient room set-up as well as space partitioning strategy can limit the impact of this drawback, as discussed in Sect. 5.

To illustrate the application of the our localization approach to the devised virtual training system in construction, the rendered views corresponding to four estimated camera poses from the estimated trajectory in ROOM2 are shown in Fig. 4.

5. CONCLUSIONS

Immersive spatial representation, using AR/VR, can enhance the learning experience of construction trainees by providing a simulated construction site environment whilst eliminating H&S risks, such as working from heights. The benefit accrued from this approach is that trainees can focus on mastering the task at hand in a safe environment and potentially enhance their performance. In this context, a vision-based localization approach, to be employed as a key component of a 3D Immersive Controlled Environment (ICE) for training in Construction, has been presented in this work. Due to recent developments of vision-based technologies, a significant advantage of the proposed approach is that it has the potential of delivering immersive experience of a training environment at a fraction of the cost of CAVE-type systems.

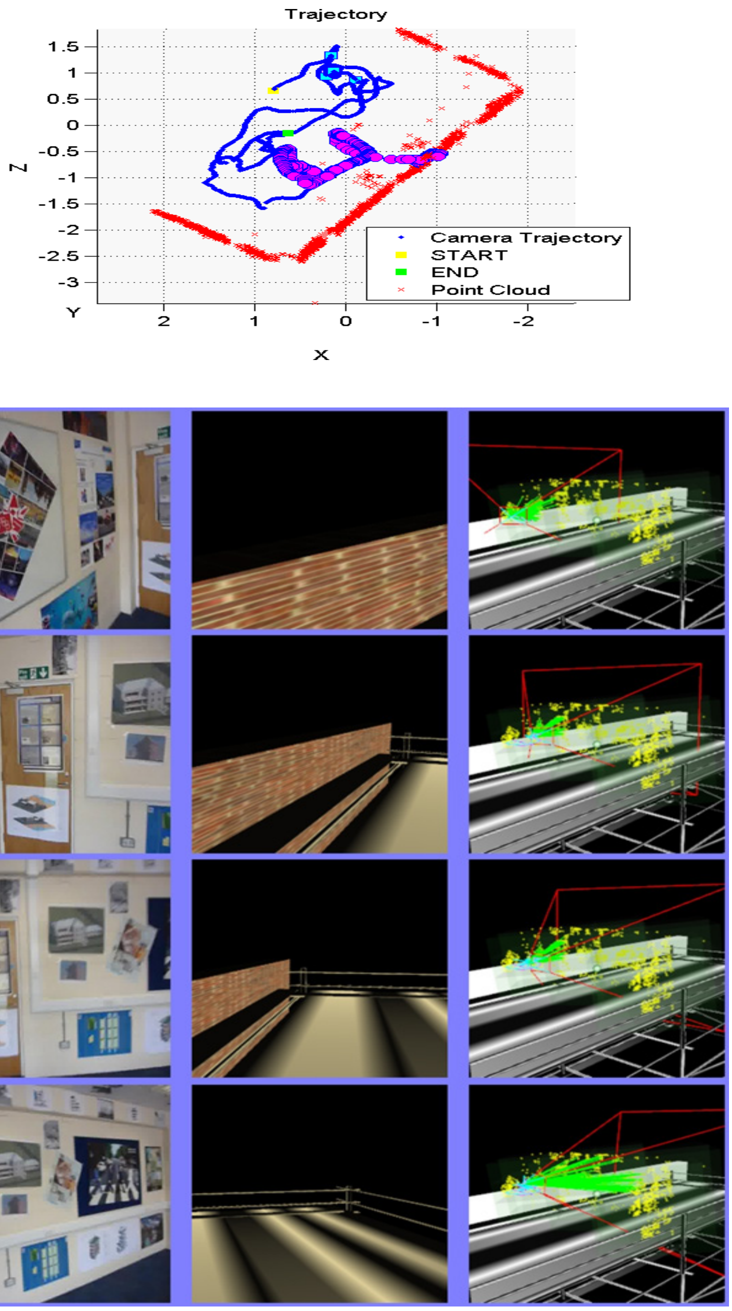


Fig. 4: Top: top view of the estimated camera trajectory for ROOM2. Magenta circles correspond to a trait of the camera path covering poor textured areas (room's ceiling). Bottom: rendered views corresponding to four estimated camera poses (cyan squares on the trajectory).

The approach consists of two stages. The first off-line reconstruction stage performs the reconstruction of a 3D visual map of the training room, covered with textured pictures (posters), from a sequence of images. The second stage aims at estimating the trainee's position and orientation within the training room during the operational stage, by registering images, acquired by a camera integral to the trainee's head, with respect to the 3D visual map. Several strategies have been devised to preserve robustness at an acceptable frame rate, including a feature tracking strategy. The performance of our method has been assessed on real video sequences of a training room, showing promising results in terms of robustness and time performance. Moreover, their analysis has shown the main current limitations, suggesting feasible strategies to overcome them. In particular, our analysis has yielded the following conclusions:

- The current setup of the training room includes poorly textured areas that have led to failed camera localization. To reduce the risk of such situation, the training room should be sufficiently covered, with textured pictures in almost all its parts. The spatial analysis of the visual map obtained from the reconstruction stage and the use of an octree, to select spatially distributed visual features during the on-line phase (as proposed in (Tingdahl et.al 2012, Carozza et al. 2012)), could also be employed to improve robustness.
- The current implementation of our approach can be directly optimized in order to speed up significantly the process toward real-time performance. The use of an octree can speed up the retrieval of strongest features distributed in the camera frustum during the matching and tracking phases, eliminating for example the need of the slow non-maxima suppression stage employed at the moment. Furthermore, GPU processing could further accelerate many of the on-line processes, especially matching and pose computation.
- The current vision-based approach could benefit from integration with INS systems (Ligorio and Sabatini 2013). The INS could be used to provide initial estimates of the head pose at a high frame rate, which would be beneficial, especially in the case of fast motions.

6. ACKNOWLEDGEMENT

We are grateful to the Construction Industry Training Board (CITB) for funding this project. The views and opinions expressed by the authors of this publication are those of the authors and do not necessarily reflect those of CITB.

7. REFERENCES

Abdel-Wahab M.S. (2012) Rethinking apprenticeship training in the British construction industry, *Journal of Vocational Education & Training*, Vol. 64, No. 2, 145-154.

ACT (2009), Advanced Construction Technology Simulation Centre, Coventry UK, http://www.act-uk.co.uk/.

Bassanino M., Kuo-Cheng W., Jialiang Y., Khosrowshahi F., Fernando T., Skjærbæk, J. (2010), The Impact of Immersive Virtual Reality on Visualisation for a Design Review in Construction, *Information Visualisation (IV), 2010 14th International Conference*, 585-589.

Bay H., Ess A., Tuytelaars T. and Van Gool L. (2008) SURF: Speeded Up Robust Features, *Computer Vision and Image Understanding (CVIU)*, Vol. 110, No. 3, 346—359.

Bosché F., Tingdahl D., Carozza L., Van Gool L. (2012), Markerless vision based Augmented Reality for enhanced project visualization, *ISG*ISARC2012*.

Bouguet J. I. (2004) Camera Calibration Toolbox for MATLAB. www.vision.caltech.edu/bouguetj/calib_doc/

Bundler (2006) http://phototour.cs.washington.edu/bundler/.

Carozza L., Tingdahl D., Bosché F., and Van Gool L. (2012) Markerless vision-based augmented reality for urban planning, *Computer-Aided Civil and Infrastructure Engineering (CACAIE)*, to appear (published online).

Cruz-Neira C., Sandin D. J., DeFanti T. A., Kenyon R. V., and Hart J. C. (1992) The CAVE - audio visual experience automatic virtual environment, *Commun. ACM*, Vol. 35, No. 6, pp. 64-72.

Dalgarno B. and Lee M. (2010) What are the learning a affordances of 3-d virtual environments?, British Journal of Educational Technology, vol. 41, pp. 10-32.

de Vries B., Verhagen S., and Jessurun A. J. (2004) Building management simulation centre, *Automation in Construction*, Vol. 13, 679-687.

Dong Z., Zhang G., Jia J., H. Bao (2009) Keyframe-based real-time camera tracking, *IEEE 12th International Conference on Computer Vision*, 1538-1545.

Feng Zhou, H.B.-L. Duh, Billinghurst M. (2008) Trends in augmented reality tracking, interaction and display: A review of ten years of ISMAR, *Mixed and Augmented Reality ISMAR 2008. 7th IEEE/ACM International Symposium on*, 193-202.

Gauglitz S., Höllerer T. and Turk M. (2011) Evaluation of Interest Point Detectors and Feature Descriptors for Visual Tracking, *International Journal of Computer Vision*, Vol. 94, No. 3, 335-360.

Hartley R. and Zisserman A. (2003) Multiple View Geometry in Computer Vision (2 ed.), Cambridge University Press, New York, NY, USA.

InterSense IS-900 Wide Area Precision Motion Tracker. http://www.isense.com

Klein G. and Drummond T. (2003) Robust Visual Tracking for Non-Instrumented Augmented Reality, Proc. *Second IEEE and ACM International Symposium on Mixed and Augmented Reality (ISMAR'03)*, 113-122.

Lau Y. K. H., Chan, L. K. Y. and Wong, H K. (2007). A virtual container terminal simulator for the design of terminal operation, *International Journal on Interactive Design and Manufacturing*, Vol. 1, No. 2,107–113.

Ligorio G. and Sabatini A.M. (2013) Extended Kalman filter-based methods for pose estimation using visual, inertial and magnetic sensors: comparative analysis and performance evaluation, *Sensors*, Vol. 13, No.2, 1919-41.

Lim Hyon, Sinha S.N., Cohen M.F., Uyttendaele M. (2012) Real-time image-based 6-DOF localization in large-scale environments, *2012 IEEE Conference on Computer Vision and Pattern Recognition (CVPR),* 1043-1050.

Lowe D. G. (2004) Distinctive Image Features from Scale-Invariant Keypoints. *Int. J. Comput. Vision*, Vol. 60, No. 2, 91-110.

Perea L., How J., Breger L., Elosegui P. (2007) Nonlinearity in sensor fusion: Divergence issues in EKF, modified truncated SOF, and UKF, AIAA Guidance, Navigation, and Control Conference (GNC- AIAA-2007-6514).

Pintaric T. and Kaufmann H. (2007) Affordable Infrared-Optical Pose Tracking for Virtual and Augmented Reality, *IEEE VR Workshop on Trends and Issues in Tracking for Virtual Environments,* 44 - 51.

Skrypnyk I., Lowe D.G. (2004) Scene modelling, recognition and tracking with invariant image features, *Mixed and Augmented Reality (ISMAR 2004), Third IEEE and ACM International Symposium on*, vol., no., pp.110-119.

Snavely N., Seitz S. M., Szeliski R. (2007) Modeling the World from Internet Photo Collections, *International Journal of Computer Vision*, Vol. 80, No. 2, 189-210.

Tingdahl D., De Weerdt D., Vergauwen M., Van Gool L. (2012) WEAR++: 3D Model Driven Camera Tracking On Board the International Space Station, *International Conference on 3D Imaging*.

Vuzix, http://www.vuzix.com/home/, accessed March 2013.

Wang X., Dunston P.S., Skiniewski M. (2004) Mixed Reality Technology Applications in Heavy Construction Equipment and Operator Training, *21st International Symposium on Automation and Robotics in Construction (ISARC 2004)*, 393-400.

Welch G., Bishop G., Vicci L., Brumback S., Keller K., Colucci D. (2001) High-Performance Wide-Area Optical Tracking: The HiBall Tracking System, *Presence: Teleoperators and Virtual Environments*, 2001, Vol . 10., No. 1, 1-21.

Woodward C., Hakkarainen M., Korkalo O., Kantonen T., Aittala M., Ranio K. and Khknen K. (2010) Mixed reality for mobile construction site visualization and communication, *International Conference on Construction Applications of Virtual Reality (CONVR)*, 35-44.

Yeh K., Tsai M., and Kang S. (2012) On-Site Building Information Retrieval by Using Projection-Based Augmented Reality, *J. Comput. Civ. Eng.*, Vol. 26, No. 3, 342–355.

SAVES: A SAFETY TRAINING AUGMENTED VIRTUALITY ENVIRONMENT FOR CONSTRUCTION HAZARD RECOGNITION AND SEVERITY IDENTIFICATION

Ao Chen

Virginia Tech, Vecellio Construction Engineering and Management Group, Via Department of Civil and Environmental Engineering and Myers-Lawson School of Construction, USA

Mani Golparvar-Fard

University of Illinois at Urbana-Champaign, Urbana, Department of Civil and Environmental Engineering, USA

Brian Kleiner

Virginia Tech, the Myers-Lawson School of construction,USA

ABSTRACT: *One of the most challenging aspects of health and safety (H&S) management for construction sites is ensuring that workers can predict, identify, and respond to potential hazardous conditions before they are exposed. While OSHA addresses the need for enforcement of comprehensive H&S training programs, many safety training programs still do not include hazard recognition or systematic preparations for the avoidance of unsafe conditions. From a scientific standpoint, we currently lack the knowledge of discovering the most efficient training styles for safety and also understanding why and how these styles of training can influence the post-training activities. To address these needs, an Augmented Virtuality(AV) training environment named System for Augmented Virtuality Environment Safety (SAVES) was designed and is presented in this paper. SAVES which integrates a Building Information Model (BIM) with photographs of typical energy sources on a jobsite, allows trainees to control and navigate an avatar within such AV environment. Within the AV environment, the user can conduct a set of interactions with the environment and accomplish multiple instruction and task-based training scenarios. These scenarios include detection of ten types of hazard and/or energy sources at three levels of severity. The energy sources which in SAVES are embedded in forms of 3D elements and 2D imagery are designed to elevate the safety awareness of the users, enable them to predict and identify various types of hazards, and assess their level of severity. To fully document the experience of the users, during each exercise, trainees' choices, time for decision-making and corresponding prevention plan are documented in the system. The complete process of design, development, implementation and results analysis of SAVES is presented.*

KEYWORDS: *Safety, Training, Virtual Reality, Hazard Recognition*

1. INTRODUCTION

Construction is one of the most dangerous and hazardous industries in the world. According to the Bureau of Labor Statistics released in 2012, 780 construction related fatalities and more than 4,000 recordable accidents were reported in the United Sates. Even though the total number of fatalities and ratio of injuries are keeping decreasing since 2009, construction still ranks the 3rd most unsafe industry after agriculture and transportation. Most accidents and injuries were caused by human error and unsafe actions due to the failure of following safety programs. Whereas, the rate of safety program improvement has slowed substantially in recent years. Many construction companies which treat safety as their central value have stated strong desire for any novel method that speed up safety improvement. Carter and Smaith (2006) and CDC (Center for Disease Control and Prevention 2012) have stated that construction workers are lack of rapid hazard recognition ability in a complex working environment. Hazard recognition is the prerequisite to build all other safety procedures. Without a sufficient awareness of hazard recognition, even the best safety program will not touch its expectation.

Construction workers are highly vulnerable to on-site accidents. Recent reports show that fatality rate in construction site is about three times higher than the overall national average (OSHA 2012). Such high rate

---

Citation: Chen, A., Golparvar-Fard, M. & Kleiner, B. (2013). SAVES: a safety training augmented virtuality environment for construction hazard recognition and severity identification. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

somehow happens due to the inadequate skills of hazard recognition and low respond efficiency to potential hazards in a complex environment. As shown in figure 1, a framework of the typical safety program which focusing on hazard recognition is presented. As one can see, an injury will actually occur when 1) a hazard is presented and 2) worker just happens to be exposed under the range of hazard, and 3) S/he is in the absence of adequate hierarch controls. As indicated in Figure 1, those hazards that not included in the perception and risk assessment process will not be preemptively recognized. This often causes the accidents even though the safety program was well planned. Typically, hazards in construction usually are associated with jobs and most workers will use their experience to identify and make the decision. Unfortunately, new workers usually are lack of adequate hazard predicting expertise and skilled workers adapt unsafe procedures to meet the productivity demands. For the purpose of enhancing their awareness of hazard recognition, company often offers formal hazard recognition training programs. Current training methods are usually based on conformist teaching instructions that already proofed making limited engagement with workers, especially for those younger workers.

In response to this urgent need, this paper explored a new hazard recognition training strategy in a multi-phase study. An augmented virtuality (AV) environment was developed and tested with essential psychology, information cognition and behavioral theories. To study how this training method improve the hazard recognition ability, this paper employed qualitative survey, quantitative hit-matrix and multiple baseline testing methods. The following sections will illustrate the development of such AV environment, filed experiment, data analysis, discussions and conclusions in detail.

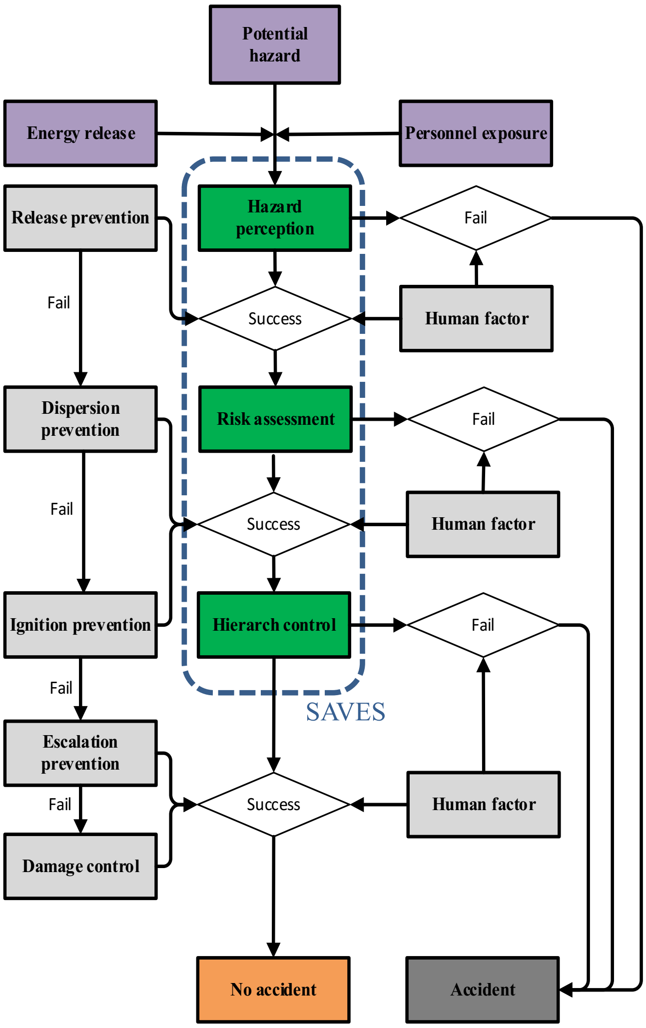


Fig.1 Framework of Hazard Recognition

2. BACKGROUND

Many methods have been studied and a lot of tools are developed to improve the awareness of hazard recognition in construction. Such methods and tools can be categorized either predictive methods or reactive methods. The first method contains scenario-structure that workers mentally construct and visualize the activities then completing detailed work missions. Based on the different activities, workers attempt to identify all hazards. Such method includes job hazard analysis, task analysis, and safety planning. Despite the huge contributions they offered, such methods have some inherent limitations like isolation, biased assumption and higher safety knowledge requirement. These methods focus on the isolated activities fail to recognize additional hazards that may arise because of the job change, complexity in construction and working environment variations (Rozenfeld et al. 2010). Besides, those methods make a pre-judgment that assume all the workers can correctly predict the work procedures and associated hazards with those procedures as well (Fleming 2009).

The reactive method usually relies on experience to determine potential hazards for a given work-setting. Often, company summarizes the reports from past projects and disseminates the material through training which involves conventional instruction. Like the first method, the reactive methods have various drawbacks. First, such methods usually do not include near miss and latest incidents (Dong et al. 2011) and reports are not thorough enough for future improvement. Second, such accident records reflect only a small subset of potential scenarios (Rozenfeld et al. 2010). Third, in a fully complex environment like construction site, specifying accidents across different setting is impossible. Finally, transferring this enormous amount of information to workers using inefficient instructional methods is unrealistic (Fleming 2009).

Thus, in order to ensure effective learning, hazard recognition training programs must be tailored to the learning styles of the workers. Unfortunately, traditional lecture-based training such like videos and lectures only keep 5% retention rate. And the trainee stays in a passive role to receive such safety information which leads to ineffective training outcomes. Workers learn better when the principles of andragogy are applied and they are involved in building context, setting objectives, cooperatively and interactively delivering instructional material, and form plans (Knowles et al. 2012). Methods that encourage active participation and visual learning are particularly effective and brings at least 75% retention rate. Given these factors, many public agencies and companies address the urgent needs and seek more positive methods to approach the effective safety training. NIOSH had mentioned this necessity that construction workers needed new training materials. Videos or lectures could not be the only resources (NIOSH, 2002). Other industries like Mine H&S Administration (MSHA), already adapted VR as training tool for safety. The information and skills obtained from VR training could be transferred to the real world in a more expressive and realistic way than acquired by applying more conservative, didactic training methods. Moreover, the biggest convenience was that VR permitted the trainees to experience situations that were hard or impossible to be shown in the real world. Another advantage of using VR was that it could systematically offer a wide range of possible training scenarios without suffering the high cost and risk of fielding personnel, equipment, and vehicles (Zeltzer et al., 1996).

Some VR applications were developed to help workers experience the standardized safe work procedures and specific single mission scenario was provided in such applications. (Grant and Daigle 1995, Lucas et al. 2008, Zhao et al. 2012). Besides their advantages in novelty and positive interaction, such applications didn't provide adequate freedom to users to experience diverse situations and they were lack of sufficient validations. Ku and Mahableshwarjer (2011) proposed a framework of BIM engaging with Second-Life to teach students integrated construction process. Such application maintained a well-designed stage with detailed conditions, but meanwhile, such applications attempted to bring too much information and scarified realism in display. Also, validation of correlation between designed training contents and raw data was not explained. Comparing with the natural drawbacks of Augmented Reality (AR) (e.g. impossible to put trainee to a real fully hazardous area, lack of interactive feedback) and VR (e.g. lose many realistic practice and display), Augmented Virtuality (AV) which have the advantages from both sides is proposed to answer the research questions. This research plans to examine the areas of safety in construction, hazard recognition and human centric AV development. The pedagogical goal of developing such AV environment focuses on providing some of the learning outcomes versus purely scenario driven learning outcomes such as lectures and safety videos.

3. RESEARCH METHOD

The objective of this research was to develop and examine new transformative hazard recognition strategies for safety improvement. This research aimed to develop a system that united industry best practices, BIM model and relevant theories from information cognition. This research conducted in the way of developing an AV environment system that addressed current weaknesses in safety training, planning, and execution. The proposed AV environment named SAVES(Safety for Augmented Virtuality Environment System), as shown in Figure 2. The research method and implementation plan of this study included four phases. In the first phase a comprehensive list of hazard data were collected from different resources and they were categorized and identified through knowledge-based method and safety expert meetings. In the second phase clients brought their training needs to the team and a proper BIM model was refined and imported to the SAVES. Such BIM model was the exact construction site where the trainees were working in. Once the BIM model was properly inserted to the environment, the third phase, development of training scenarios was conducted. Combining with the comprehensive benchmarking from safety regulations, best practice in industry, safety experts in the team and identified hazard data from first phase, a set of well-designed training scenarios were developed and integrated to the BIM model. The final phase the SAVES was field tested to determine its impacts on hazard recognition skill. The overall aim of this research was to experimentally test the hypothesis that a given AV training system such as SAVES could lead to a measurable increase in the proportion of hazards identified and communicated before work begins.

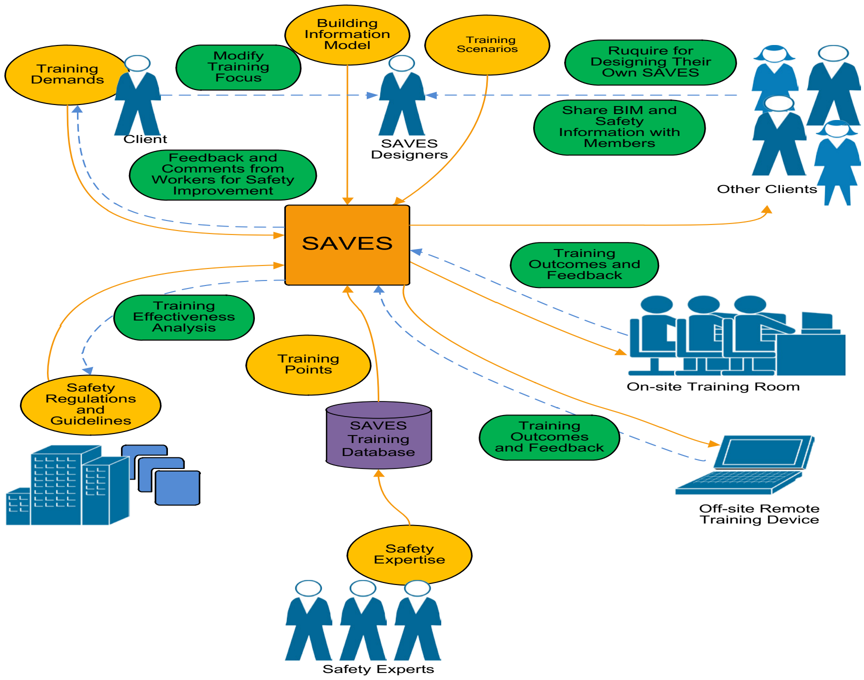


Fig. 2: Research structure of SAVES

4. DEVELOPMENT OF SAVES

4.1 Inventory of Hazard in SAVES

Safety hazards widely and randomly distributed around the whole construction site. It is hard to simply recognize the causality from each injure or fatality due to the unique and multi-factors overlapping. The meaning of the word hazard can be confusing. Often dictionaries do not give specific definitions or combine it with the term "risk". The definitions of hazard in academia are various. E.g., Rivara (2000) defined hazard as the in favor of loss. Zohar (1980) defined hazard as a combination of the possibility of unfavorable results and the related loss of a chosen decision plan due to various uncertainties in the decision making process. In this research, hazard was defined as a condition or action that had the potential for an unplanned release of, or unwanted contact with, an energy source that might result in harm or injury to people, property, or the environment (Kleiner 2012, Chevron 2012).The research team went through the documents, case studies, reports and had delivered top 10 energy source types that most easily lead to accidents and fatalities in construction. Table 1sumrizes those 10 energy types in detail.

Table 1: Definitions of energy source types

Energy Type	Definition	Energy Type	Definition
Biological	Living organisms that can present a hazard	Motion	The change in position of objects or substances
Chemical	The energy present in chemicals that inherently, or through reaction	Pressure	Energy applied by a compressed or vacuum liquid or gas
Electrical	The presence and flow of an electric charge	Radiation	The energy emitted from radioactive materials
Gravity	The force caused by the attraction of all other masses to the mass of the earth	Sound	A vibrating-cause force the energy is transferred through the substance in waves
Mechanical	The energy of the components of a mechanical system	Temperature	The measurement of differences in the thermal energy

4.2 Development of Training Scenarios

After defining the hazard types and categorizing all raw data, the next phase was to build and refine the hazard recognition scenarios. Based on the discussions of the research team, each identified hazard type was recategorized to a scale index system from 1 to 3 which indicating different severity. The smaller the number the construction behavior assigned the better safety level it had. Level 1(green) presented no observable issues been presented in the training scenario. Level 2(yellow) showed that potential hazard or/and poor practice stated in the training scenario. The last level, level 3(red), required an instant work stop to avoid foreseeable serious accidents. This color coded system could provide easy, directive signals in human information cognition process. All the information of such training elements were integrated together and those completed data were saved to the hazard information database for the use in data analysis. Figure 3 indicated a sample of training interface inside SAVES. Besides this principle criteria, the research team also realized the need to incorporate theories from human information processing and data cognition to facilitate retention of new information, motivate workers to actively participate in the hazard recognition process and improve worker hazard recognition skills. Table 2 presented the various techniques that were integrated to design the training scenarios in SAVES.

Table 2: Techniques that were incorporated in developed SAVES training scenarios

Theories	**Application inside SAVES**
Retrieval Mnemonics (Scruggs T.E. et al. 2010)	Users will be taken to a separate interface to view the hazard scenarios when they active the triggers through the navigation.
Goal-Setting (Locke et al. 1981)	A score bar always presents the current accumulated score in the main interface. Such approach is to motivate individuals to direct action towards goal attainment
Feedback (Renn and Fedor 2001)	A feedback section is placed in each training scenario to allow users input their feedback and plan of hierarch controls.
Self-regulation (Latham 2007)	A total of 68 scenarios are inserted to SAVES and a hint system is available for users. It ups to users to choose whether they can rely on the helper or use their own experience
Game-theory (Zyda 2005)	SAVES is a game engine-based system which making learning process more fun and more engaged.
Situational awareness (Endsley et al. 2011)	A augmented real hazardous picture is integrated in each scenario which fully enhancing user's capacity to perceive, comprehend and respond to hazardous stimuli
Visual Cues (Hsiao and Simeonov 2001)	A master key answer of each training scenario is given in the end of the completion. It prompts individuals to respond to such signal sensors in the feedback section.
Real-time signal detection	Facilitates responding to specific stimuli when detected, thus reducing the need to forecast or predict future conditions

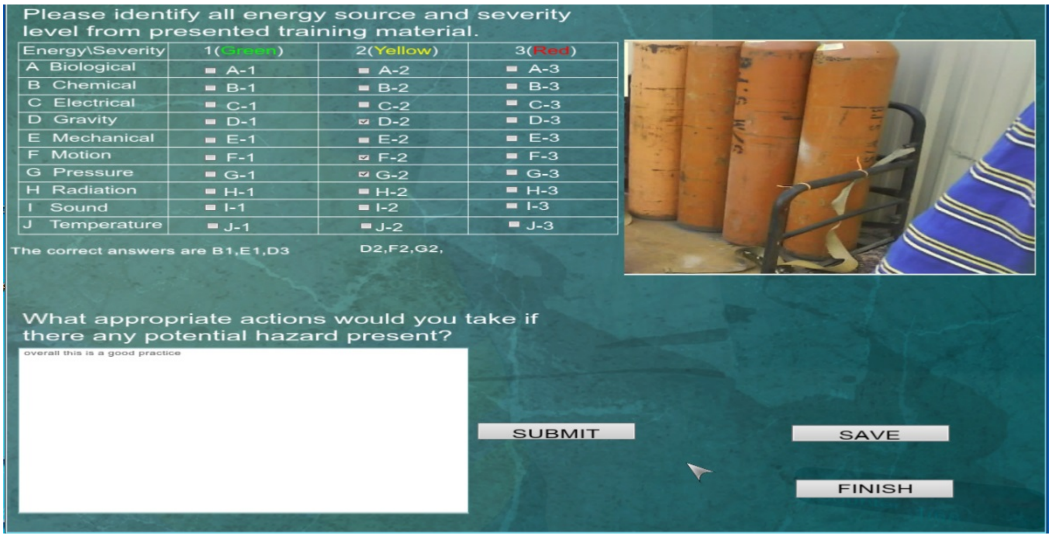


Fig. 3: Snapshot of developed training scenario

4.3 Development of SAVES Environment

The main research objective was to develop and test whether the SAVES improve workers' awareness of hazard classification, severity identification and ability of taking proper reaction plan. In order to approach such goals, the first key part was designing proper avatar which containing essential features and complete gestures tree. One hypothesis of this research was that a fully realistic and open-to-search BIM construction site provides greater benefits than a purposely constrained virtual training scenario. Besides, for the purpose of highly presenting the life replica in the AV environment, it was important to design a proper avatar for trainee to interact with all virtual contents. Thus, research team had reviewed the documents from OSHA regulations and extracted the safety information about entering to construction site as well as required Personal Protective Equipment (PPE) for working in the job site. As shown in Figure 4, the finalized avatar was a well-designed highpoly character with all PPE patterns including hard hat, construction boots, safety goggles, safety vest, ear muff and long sleeve working uniform, etc. This highploy avatar had more than 98,206 polygons and additional about 80,000 polygons for PPE. Such high-quality polygons maximized the realism in 3D and optimized performance in SAVES.

The second key part included a well-constructed BIM model as a training stage. Comparing with traditional VR scene, Building Information Model provides more realistic display and vivid experience. In order to correctly make BIM project to SAVES, the traditional 2D construction plan needed to be converted to 3D in Revit firstly. The building plans were converted to appropriate sizes and formats then they were imported to Maya to be assigned the texture rendering ID. The model pieces were built up in a sequence of sections which reflecting the construction stages. By structuring the environment in this approach it permitted the construction site to be linked with more detailed texture and material information as well as other diverse exterior recourse. This was exploited through the use of "UV mapping" and GFX method. All elements which correctly having texture ID were rendered and represented with UE3 in SAVES. Also, by linking the separate parts together via dynamic loading flow, it is easy to upgrade SAVES accompanying with the real construction schedule and progress in the future.

Fig. 4: View of Avatar and SAVES

5. EXPERIMENT SETUP AND FIELD TESTING

To emerge the designed safety training elements to the environment, a total number of 600 hazard datum were successfully decided and categorized. Around 300 hazard datum of sub-energy types have been recorded as well. These datum were used to develop the training scenarios which aided to be set up in SAVES for different needs. SAVES let trainees interact in situ in a manner similar or even exact to the situations as they would be on-site. Training scenarios were envisioned as small set exercises under the OSHA regulations and best industry practices. Comparing with such instruction-based module, task-based training module required trainees to use their safety knowledge to search through the whole stage for training spots and then recognized the hazards types, severity levels and corresponding action standards inside each training scenarios. In addition, trainees were tested to make a proper plan of hierarch control in each scenario. SAVES was divided into 3 training stages which were indoor-work environment, outdoor-work environment and construction equipment zone. Figure 4 presented two partial views of the completed training system. The SAVES contained 68 training scenarios in total around all three stages. All the training modules were scored and score was shown to the trainee in main screen in real time.

The field testing were taken in two different facilities located in south of the United States. Each time the testing was performed as a group training. Each group had at least 5 persons and everyone was asked to fill out the questionnaire after training. Their pre-activities and post-activities were also recorded for effectiveness analysis.

6. DISCUSSION

A qualitative and a quantitative analysis have been conducted after field testing. A survey was sent to the trainees who experienced SAVES. A total number of 36 replied questionnaires were received. The survey had five major categories of questions which included the attitudes of such AV system as a training method, the degree of such training involvement, agreement of training scenarios inside SAVES, confidence of safe working after such training, and comparison with other training methods they had before. The feedback and comments of SAVES were also collected for the purpose of new version development. After analyzing all received questionnaires, statistical results showed that 98% users had positive attitudes about SAVES and 100% users indicated that they were highly engaged with this AV system. As for training effectiveness, 94% users agreed the training contents that presented in SAVE fitting to their real job situations. About 97% users believed that they had more safety awareness and confidence after implementing SAVES.

The quantitative analysis was conducted based on the training results stored inside SAVES. In this research, Signal Detection (SD) theory was used to measure the hazards or energy sources which lead to the most incorrect discriminations during training session and how the workers to detect such hazardous cues in their real job environment after implanting SAVES.

SD theory provides a precise language and graphic notation for analyzing a target stimulus from random energy patterns and exploring the decision making under difficult perceptual judgments due to a great amount of complexity and uncertainty. Such applications of SD theory can be referred to the worker's safety awareness of hazard recognition ability and what energy sources could mislead workers to make incorrect safety decisions in real job environment. SAVES studies SD problem in construction industry through research the ability of a worker to identify a potential injury or hazard in such complex environments. As shown in Equations 1 and 2, SD_t was measured the proportion of stimuli that were incorrectly discriminated. The goal was to minimize such proportion and maximize the correct identification and rejection (see Table 3 for details). SD_{t1} was the measurement to measure the accuracy under the situation of all signals were presented when the value SD_t was too high.

$$SD_t = (b + c)/\,(a + b + c + d) \qquad \text{(Eq.1)}$$

$$SD_{t1} = a/\,(a + c) \qquad \text{(Eq.2)}$$

Table 3: Signal Detection Matrix (SDM)

	Signal Present	Signal Absent
Signal Detected	Correct identification (a)	False Alarm (b)
Signal NOT Detected	Miss (c)	Correct rejection (d)

As summarized in Table 4 and 5, the average accuracy of overall training was 84% and the average hazard responding time was 1.5 minutes. However, among 36 users in total, they often made incorrect discriminations with mechanical hazard (level2), chemical hazard (leve2), electrical energy (level1), sound energy (level1) and gravity energy (level1). This suggested the research participating companies should pay more particular attentions to train their employees in such weak points in their next training cycle.

Table 4: Summary of accuracy when all signals presented (SD_{t1})

	Bio	Che	Elec	Gra	Mech	Mot	Pres	Rad	Sod	Temp
Lv1	0.019	0.019	0.019	0.077	0.135	0.038	0.038	N/A	0.019	0.019
Lv2	N/A	0.038	0.019	0.058	0.019	0.135	0.019	N/A	N/A	0.019
Lv3	0.019	0.019	0.019	0.115	0.019	0.019	0.019	0.038	0.019	0.019

Table 5: Summary of incorrect signal detection (SD_t)

	Bio	Che	Elec	Gra	Mech	Mot	Pres	Rad	Sod	Temp
Lv1	0.026	0.013	0.128	0.077	0.051	0.013	N/A	N/A	0.077	0.013
Lv2	0.013	0.064	0.013	0.026	0.115	0.051	0.013	N/A	0.051	0.026
Lv3	0.026	0.038	0.038	0.026	0.013	0.051	0.026	N/A	0.013	N/A

Also, workers seemed like very sensitive to the energy sources of gravity, mechanical and motion. They could make most correct discriminations when such signals were presented and many of them did not make the false alarm for such instances. That might indicate that those workers could be highly aware of falls, slippery, inadequate housekeeping, equipment contact, cave-in and struck-by in their real job environment.

As illustrated before, the post-training activities were recorded and the follow-up observation (see Figure 5) showed that the pre-SAVES and post-SAVES using real hazardous scenarios revealed significant improvements ($p < 0.05$) in the proportion of hazards recognized. Crew 1, 2 and 3 demonstrated an increase in hazard recognition of 41%, 34% and 44, respectively. All those outcomes and results indicate that SAVES could be very efficient in training workers' ability of hazard recognition and it has a huge potential of usage in construction as a novel method to motivate workers and companies having different safety experience.

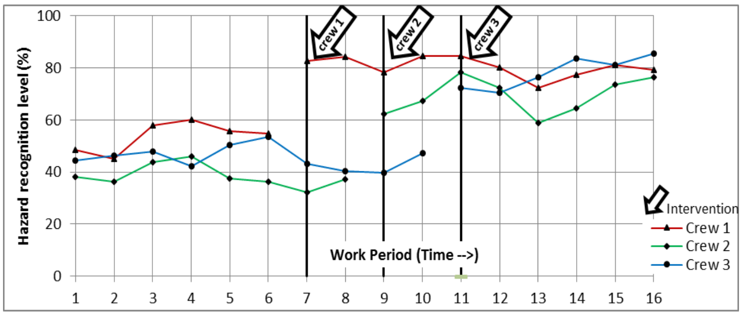


Fig. 5: Post –SAVES intervention results

7. CONCLUSIONS

This research has designed and developed SAVES to study the potential of such AV system as an effective to train and improve workers' hazard recognition skills. Furthermore, out of existing training methods, such practical exercises can provide the most transferable safety knowledge back to the workers. Such "learning by doing" style creates a clean mapping between site hazards and their recognition. The correlation allows practitioners to exercise recognition of site hazards more rapidly and in turn avoid fatalities and injuries through improvement of situational awareness.

SAVES provides a quick bidirectional communication platform to both management and workers. The company can use such results and feedbacks from SAVES to modify their initial training focus in order to improve the missed safety parts. Besides the advantage of short modeling time, SAVES is also expandable and upgradeable alone with construction schedule and real progress so as to provide the best training effort.

The research analysis shows that SAVES is able to provide efficient training effort. Post-SAVES activity observation indicates that all three participating groups can significantly recognize hazardous cues on site and make right actions according to different severity levels. The average of hazard recognition rate can increase up to 40% comparing with pre-SAVES activities. The qualitative questionnaires also show that workers can quickly accept SAVES with little problem and they are confident that safety knowledge are enhanced by interacting with SAVES. Workers can easily recognize the energy sources of gravity, mechanical and motion during the training. Such results imply those workers may have much less risk when their jobs relate to the hazards of falls, slippery, housekeeping, equipment contact, cave-in and struck-by. The top 5 hazards with severity levels which having high ratio of incorrect discriminations are identified as well. SAVES makes safety practical learning more active and engaging since it allows for safe simulation of real-life events in a digital environment that might otherwise be too dangerous or expensive. Construction workers, supervisors, owner representatives, contractors and society will benefit from such advantages.

The limitation of this work could be the lack of across comparison with other hazard recognition training methods. The undergoing research starts to address this limitation and the future work will focus on developing the weighting index and deciding the complexity coefficient for better training accuracy measurement. Also, future work may study the best way to maximize the benefits of SAVES and studying trainees' hazard discrimination tolerance.

8. ACKNOWLEDGEMENT

This research was funded by Construction Industry Institute. The authors want to thank Dr. Matthew Hallowell to help us in the post-activity research and other persons involved in the research. Finally, special thanks to Chevron Company for their kindness help.

9. REFERENCES

Carter, G., and Smith S.D. (2006). 'Safety hazard identification on construction projects', *Journal of Construction Engineering and Management*, Vol. 132, No.2, 197-205.

Centers for Disease Control and Prevention (2012) *Construction* , viewed 15 March 2012 http://www.cdc.gov/niosh/construction/

Dong, X. S., Fujimoto, A., Ringen, K., Stafford, E., Platner, J. W., Gittleman, J. L., Wang, X. (2011). 'Injury underreporting among small establishments in the construction industry', *Am. J. Ind. Med.*, Vol. 54, 339-349.

Endsley, M. R., Bolté, B., Jones, D. G. (2011). 'Designing for situation awareness : An approach to user-centered design', CRC Press, Taylor & Francis, London.

Hsiao, H., and Simeonov, P. (2001). 'Preventing falls from roofs: A critical review'. *Ergonomics*, Vol 44, No.5, 537-561.

Knowles, M. S., Holton III, E. F., Swanson, R. A. (2012). The adult learner the definitive classic in adult education and human resource development, Routledge, New York.

Ku, K and Mahabaleshwarkar,S, P. (2011). 'Building interactive modeling for construction education in virtual worlds', *ITCon 2010*, Vol.16, 189-208.

Latham, G. P. (2007). Work motivation : history, theory, research, and practice, Sage Publications, Thousand Oaks, Calif.

Locke, E. A., Shaw, K. N., Saari, L. M., Latham, G. P. (1981). 'Goal setting and task performance: 1969–1980'. *Psychol. Bull.*, Vol. 90, No.1, 125.

Lucas, J., McMahan, R., Engle, R., Bowman, D., Thabet, W., Scafrik, S, and Karmis, M. (2008). 'Improving health and safety through conveyor system training in a virtual environment', International Future Mining Conference, 9-11 June, 2008. Sydney, Australia.

Mine Safety and Health Administration (MSHA). (1998). A new focus in MSHA, viewed 23 March 2012,http://www. msha.gov/TRAINING/EPDFS/EPDFS.pdf

National Institute for Occupational Safety and Health (NIOSH). (2002). Recommendations to the U.S. Department of labor for changes to hazardous orders, viewed 18 March 2012, http://www.cdc.gov/niosh/docs/nioshrecsdolhaz/pdfs/dol-recomm.pdf

Occupational Safety and Health Administration (OSHA). (2012). *OSHA Trade News Release*, viewed 13 March 2012, http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=NEWS_RELEASES&p_id=21636

Renn, R. W., and Fedor, D. B. (2001). 'Development and field test of a feedback seeking, self-efficacy, and goal setting model of work performance'. *Journal of Management*, Vol. 27, No.5, 563-583.

Rivara, F., & Thompson, D. (2000). 'Prevention of falls in the construction Industry: Evidence for Program Effectiveness', *American Journal of Preventive Medicine*, Vol.18, No.4, 23-26.

Rozenfeld, O., Sacks, R., Rosenfeld, Y., Baum, H. (2010). 'Construction job safety analysis'. *Saf. Sci.*, Vol. 48, No. 4, 491-498.

Scruggs T.E., Mastropieri M.A., Berkeley S.L., Marshak L. (2010). 'Mnemonic strategies: evidence-based practice and practice-based evidence'. *Intervention Sch.Clin.Intervention in School and Clinic*, Vol. 46, No.2, 79-86.

Wang, Y., Goodrum, P. M., Haas, C., Glover, R., Vazari, S. (2010). 'Analysis of the benefits and costs of construction craft training in the united states based on expert perceptions and industry data'. *Constr. Manage. Econ.*, Vol. 28, No.12, 1269-1285.

Zeltzer, D., and Pioch, N.J. (1996). 'Validation, verification of virtual environment training systems', *IEEE 1996 Virtual Reality Annual International Symposium,* Dayton, Ohio, 123–130.

Zhao,D, Thabet,W, McCoy,A and Klienr,B. (2012). 'Managing electrocution hazards in the US construction industry using VR simulation and cloud yechnology', *eWork and eBusiness in Architecture*, *Engineering and Construction*, ECPPM 2012, 759-764.

Zohar, D., (1980). 'Safety climate in industrial organizations: theoretical and applied implications', *Journal of Applied Psychology* , 96-102.

Zyda, M. (2005). 'From visual simulation to virtual reality to games'. *Computer*, Vol. 38, No. 9, 25-32.

AN INTERACTIVE DATA VISUALIZATION SYSTEM FOR FLOOD WARNINGS IN TAIWAN

Er-Xuan Sung, Meng-Han Tsai & Shih-Chung Kang
Department of Civil Engineering, National Taiwan University, Taiwan

ABSTRACT: *This paper reports on the development of an Interactive Data Visualization System (IDVS) for flood warnings. Information from multiple sources, such as precipitation, geographical conditions, and the alert threshold, is collected in the system. Users of the system are able to manipulate the information to enhance their understanding of the flood potential. This can help them make timely and correct decisions. We develop four interactive functions: (1) Datatip, (2) Dashboard, (3) Data brushing, and (4) Dynamic queries. A Datatip displays all related data of a particular point or an area when the mouse hovers over. A Dashboard comprises multiple views, allowing users to manipulate and compare the information. The Data brushing function highlights the selected dataset in other views when users choose specific information in which they would like to gain deeper insight. The Dynamic query function provides a scroll bar for users to explore information by dragging the slider. By integrating the four functions, the system provides users with dynamic exploration and intuitive operation. We use data collected from a flood occurring in Taiwan on 10th June 2012 to validate our system. The results show that the IDVS can effectively help integrate decision-making information in real time. The interaction between related information provides users with insightful and versatile views, which can enhance decision-making.*

KEYWORDS: *data visualization, interactive interface, flood informatics, disaster mitigation.*

1. INTRODUCTION

Global climate change has caused the climate to tend to extremes in recent years. Using Taiwan as an example, Typhoon Morakot, formed on 5th August 2009, produced an hourly precipitation exceeding 50 millimeters at two stations for 24 hours. Moreover, it broke the record of the maximum daily accumulated precipitation, 1403 millimeters. Typhoon Megi, formed on 21th October 2010 caused a record-breaking hourly precipitation and daily accumulated precipitation at Su'ao station, 181.5 millimeters and 939.5 millimeters respectively. During Typhoon Nanmadol, formed on 27th August 2011 the hourly precipitation at Kenting station, 122 millimeters, broke the record made by Typhoon Morakot. Floods are often the result of those huge precipitations, causing countless roads and farms in Taiwan inundated with floodwater. Therefore, we should pay more attention to flood prevention and response.

Early warning is described as the process of detecting a possible threat using forecasting models and decision makers. Before taking any action, the decision makers must identify the possible threat (Boin *et al.*, 2005). The emergency response teams in some flood prone areas have designed their own standard procedure which provides early warning for natural disasters. For instance, the Environment Agency and the Meteorological Office in UK launched a service named Extreme Rainfall Alert (ERA) (Flood Forecasting Center, 2010). The service is based on the average 1-in-30 year storm rainfall-intensity thresholds. When the national rainfall threshold for severe urban flood is exceeded, the service will provide a warning for surface water flooding. The Hydrologic Research Center (HRC) in San Diego, California of USA has developed a Flash Flood Guidance System (FFGS) that can be used as a diagnostic tool by disaster management agencies to detect flash floods (WMO, 2007). At National Meteorological and Hydrologic Services (NMHS), the same system has also been integrated into its operation along with other available data, system, tools and local knowledge to aid in determining the risk of flash flood. In the Netherlands, the Royal Dutch Meteorological Institute (KNMI) sends the rainfall risk profile consisting of different rainfall volume events as a warning message to the local districts for further analysis. When one or more risk profiles are expected to occur, an early warning will be issued (NUWCReN, 2012). The flood alert system in Marseilles, France links rainfall intensities to locally relevant flooding thresholds for floods of different estimated return periods (Deshons, 2002). The system has defined four levels of alert in accordance with rainfall intensity and accumulated rainfall. In the research of Hurford *et al.* in 2012, his research team discovered that recording flood event data would facilitate a more accurate analysis after conducting several case studies. However, the influence of using rainfall-runoff models as addressed above to predict flood potential is limited since the

---

Citation: Sung, E-. X., Tsai, M-. H. & Kang, S-. C. (2013). An interactive data visualisation system for flood warnings in Taiwan. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

computation of the model is too time-consuming to make timely decision for flood warnings. In addition, the accuracy of precipitations forecast needs to be improved. Hence, there are still many challenges to establish real-time flood warning with current technologies.

2. FLOOD WARNINGS PROCEDURE IN TAIWAN

Authorities in Taiwan have formulated two regulations, the "Disaster Prevention and Response Act" and the "Central Emergency Operation Center Operating Guidelines", for disaster early warnings. The research center for Weather Climate and Disaster Research (WCDR) at National Taiwan University (NTU) serves as a technical support of disaster preventions and responses to Taiwan Governments. Therefore, we interviewed two experts working in WCDR to understand the operating procedures for flood warnings. The overall procedure is illustrated in Fig. 1. The following paragraphs describe the components of the procedure.

1. *Field*:

There are three kinds of critical information - precipitation, alert threshold, and geographical conditions - generated by the monitoring system, the subject experts' analysis, and the statistical data, respectively, that is collected and saved in the database belonging to the WCDR.

Precipitation: Precipitation is an essential factor widely used in the meteorological field to forecast weather. According to the "Disaster Prevention and Protection Act", the Water Resources Agency of the Ministry of Economic Affairs is responsible for implementing different levels of response when the precipitation reaches three kinds of threshold. Three levels of rainfall - heavy rain, extremely heavy rain, and extremely torrential rain - have been defined based on the 24-hour accumulated precipitation in certain regions, reaching 130 millimeters, 200 millimeters, and 350 millimeters, respectively. If the 24-hour accumulated precipitation of a certain area is more than one of the latter two conditions, the experts will hold a meeting to discuss whether it is necessary to set up a CEOC.

Alert threshold: Each precipitation station has its own alert thresholds, with two different levels depending on the severity of the flood warning, level 1 alert and level 2 alert, defined by The Disaster Prevention Information Service Network of the Water Resources Agency. Level 1 Alert is established if it is continuing to rain in the flood warning area, then there may already be flooding at easy-to-flood villages and roads. If it is continuing to rain in the flood warning area, then there may be flooding at easy-to-flood villages and roads in three hours, which defines level 2 alert. In addition, alert is divided into five types: hourly precipitation, 3-hour accumulated precipitation, 6-hour accumulated precipitation, 12-hour accumulated precipitation, and 24-hour accumulated precipitation. These alert thresholds are formulated based on the experience of past flood events, the data of high flood potential districts, and the data of each rain station and its affected areas. For example, the data of 24-hour accumulated precipitation is obtained by summing the number of precipitations in the previous 24 hours. Based on the date of past flooding events, the experts can calculate the minimum precipitation value that causes flooding at each rain station, which defines the threshold of level 1 alert. Once level 1 alert is determined, level 2 alert can be defined by subtracting 10~50 millimeters from the value of level 1 alert. If necessary, both levels can be revised according to the records of future flood events. If any type of precipitation reaches its own defined alert threshold at a certain station, then a flood warning will be issued in the alert-affected areas.

Geographical conditions: Different geographical conditions may affect the flood potential. For example, the capability of pumping and drainage facilities in different areas leads to different probabilities of flooding. Meanwhile, the loading of Rainwater Drainage Systems (RDS) in different administrative regions is another indicator of flood potential. Other factors, such as low-lying areas and a full tide, may cause severe flooding.

2. *Office*:

After a certain area suffers rain and the precipitation reach the alert threshold, experts in the WCDR, the data analyzers, must monitor the weather conditions continually and analyze related data extracted from the database, such as precipitation, to judge flood potential. As soon as the precipitation satisfies the conditions of setting up a CEOC, the experts will hold meetings to aggregate relevant information to find the solution to the flood and then make reports to the executive for final decision-making. The workflow will be repeated until the flood potential drops to its lowest. The research scope is shown in Fig. 1 (frame A). This begins with the data analyzers extracting their required data from the database, followed by analysis and judgment, and then a meeting and decision-making.

The particular process regarding data gathering, which is represented by the red arrow inside frame A, will be discussed later in section 4.1.

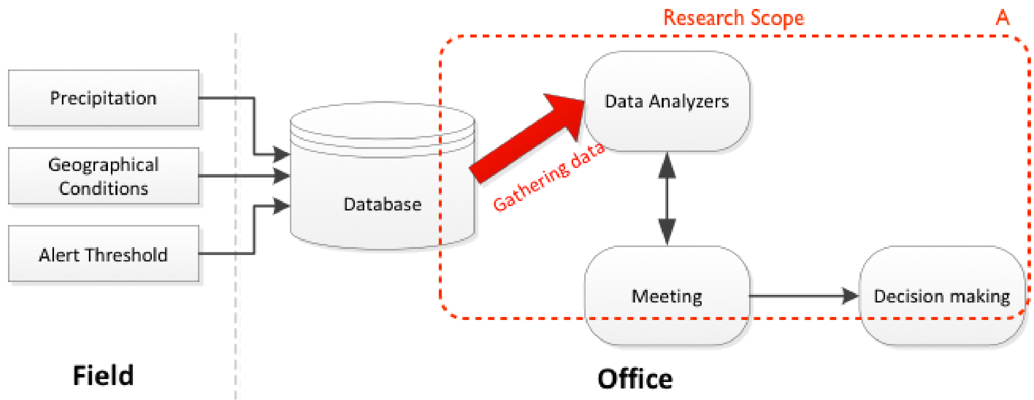


Fig. 1: Empirical model of flood warnings procedure in Taiwan.

3. DATA VISUALIZATION

Many investigators have attempted to help users extract useful information from the available data. The amount of data and information has rapidly increased over the last decade. The better-educated processes and procedures have also become quite complicated. Shneiderman (1986) mentioned that the time required by the human perceptual system to understand knowledge is less than that of the cognitive system, and that the human visual system is the fastest among the perceptual systems. The research of Crapo *et al*. (2000) indicated that humans are able to make judgments when observing a number of visual characteristics (including movement, color, size, orientation, *etc*.) without any conscious effort. Human brains depend on short-term memory and long-term memory to process the received perceptual task. Card *et al*. (1983) pointed out that images can more easily trigger the perceptual system to understand things than normal text and numbers, which aids short-term memory to a certain extent. Moreover, short-term memory can develop into a part of the long-term memory. Visualization can provide an intuitive understanding of complex data (Johansson *et al*., 2010). Utilizing visualization technology to present large amounts of data and information as images can transfer some of the work of information processing from the cognitive system to the perceptual system. Hence, the rate at which the human brain can absorb knowledge is accelerated. Visual technologies contribute to various stages of better-educated processes, providing researchers with a variety of different angles to observe the data. They can discover new knowledge by identifying possible spatial connections and the characteristic patterns in a multi-dimensional database. The man-machine interface (also known as a user interface) has made a revolutionary change in many fields, and has improved communication between the data and the end-user. Because human beings can quickly understand a visual representation of how different entities are connected and their relative positions, interface designers can take advantage of this feature to transfer some messages from cognitive systems to perceptual system (Shneiderman, 1994).

Different available visualization techniques conveying different levels of understanding are of use in different situations. In other words, visualization techniques make huge and complicated amounts of information intelligible. The common visualization techniques are divided into three categories: data visualization, information visualization, and interactivity (Khan & Khan, 2011). Data visualization is the study of the visual representation of data, which means information that has been abstracted in some schematic form, including attributes or variables for the units of information. In contrast, information visualization concentrates on the creation of approaches for presenting abstract information in intuitive ways (Thomas and Cook, 2005). Interactive visual representations of information—the basic purpose of visualization—can exploit a human's perceptual and cognitive capabilities for problem solving (Colin Ware, 2004). The goal is that a user can easily understand and interpret a huge amount of complex information.

4. RESEARCH OBJECTIVES

The objective of this research is to develop an interactive data visualization system (IDVS) that can assist experts in exploring the multi-dimensional data of a flood. To achieve this objective, we would like to develop a system that can deal with the large amount of data and provide users with an intuitive operating interface so that they can concentrate on analyzing and judging data of the latest situation and return it to the central decision-making unit. To increase the efficiency of data analysis and judgment, the system needs to reduce the time they take to explore the data. A user interface that can simultaneously present a variety of information and allow users intuitive operation can improve the performance of the flood warning. Because the flood data and geographical conditions come from different sources, the system needs to integrate them in order to obtain the best visual performance.

5. THE INTERACTIVE DATA VISUALIZATION SYSTEM

In this research, we developed an interactive data visualization system (IDVS) to help users make crucial decisions. Huge amounts of disaster-related data, which are of different types and stored in various formats, are generated from different sources. The decision makers also can use IDVS to make accurate judgments based on huge sets of disaster-related multi-dimensional data.

5.1 Gathering data

In order to present such data in more efficient ways, we divided the date into two categories in the IDVS: rainfall-related data and geographic data.

Rainfall-related data: The rainfall-related data include precipitation station numbers, recorded date and time, hourly precipitation, and accumulated precipitation in the previous 3, 6, 12, and 24 hours. The precipitation data are raw data generated by automatic precipitation monitors belonging to the Central Weather Bureau (CWB). We gathered the data source from existing databases of CWB by using SQL Server Integration Services (SSIS) platform.

Geographic data: The geographic data are collected within three different files and from different resources, including the positions of Taiwan's precipitation stations, the alert threshold based on different precipitation stations in Taiwan and the alert-affected area, and both the boundaries of Taiwan's administrative regions and Taiwan's townships. The file containing the positions of Taiwan's precipitation stations, provided by the Water Resources Agency in CSV format, comprises each precipitation station's name, longitude, and latitude. The file containing alert thresholds based on different precipitation stations in Taiwan and the alert-affected area, provided by the Water Resources Agency in CSV format, comprises each precipitation station's name, its administrative region's name, the town's name, the affected areas' names, the level 1 alert of flood warning at each station, and the level 2 alert of flood warning at each station. The file containing the boundaries of Taiwan's administrative regions and Taiwan's townships, provided by the Institute of Transportation of the Ministry of Transportation and Communications, contains TWD97 data in SHP format. The polygons representing the boundaries of Taiwan's towns are produced by inputting the package from the gathered prime data into the IDVS. Then we create an Excel file, a requirement of the package, comprising each town's serial number, each administrative region's name, and each town's name.

Finally, we converted the three CSV file formats to XLS, the same as the latter file. In this way, we can integrate the three different files. Thus, we inputted a single file composed of three spreadsheets into the IDVS.

5.2 Functions of the IDVS

In order to assist users in exploring this complicated data in more efficient ways, we develop the following four visual interactive functions:

Datatip: Datatips are tooltips showing data values or enumerations when a mouse hovers over a point, area, label, *etc*. Users can roll over various points within a graphic while the data associated with those points appears immediately in the datatip.

Dashboard: Dashboards provide a collection of multiple visual components fitted entirely on a single computer screen, including the most information needed to achieve one or more objectives, so that the information can be monitored at a glance. Interactive exploration, combined with appropriate visual representations using colors, size, and shape, can amplify human cognition and enhance information understanding.

Data brushing: If two or more views make up a dashboard, then, whenever a user selects a set of data points or just a point or area in one view, the selected dataset, point, or area in the other views will also be highlighted in real time.

Dynamic queries: Dynamic queries provide easy-to-use standard controls, such as sliders and checkboxes, to filter the data set immediately and interactively when users adjust those controls and the results appear on the display.

5.3 System architecture

The overall composition of IDVS is illustrated in Fig. 2. It has a two-layer structure comprising a user interface layer and a data layer. The blocks represent the major components or functions in both layers. The arrows between each layer represent the direction of communication or the flow of data. The user interface layer provides users with functions to directly manipulate and interact with each view in a dashboard, which can present the results in a visual way. The data layer consists of four components. There are two kinds of database, historical and real-time. In this paper, we extract precipitation data from historical database which was collected during a flood event from 10th June to 16th June 2012 (called the 610 flood). The data processor is responsible for extracting data from the database and satisfies the demand of view table; and the view table generates elements in the dashboard. During the user phase, users can manipulate elements in the dashboard directly and obtain synchronous feedback visually.

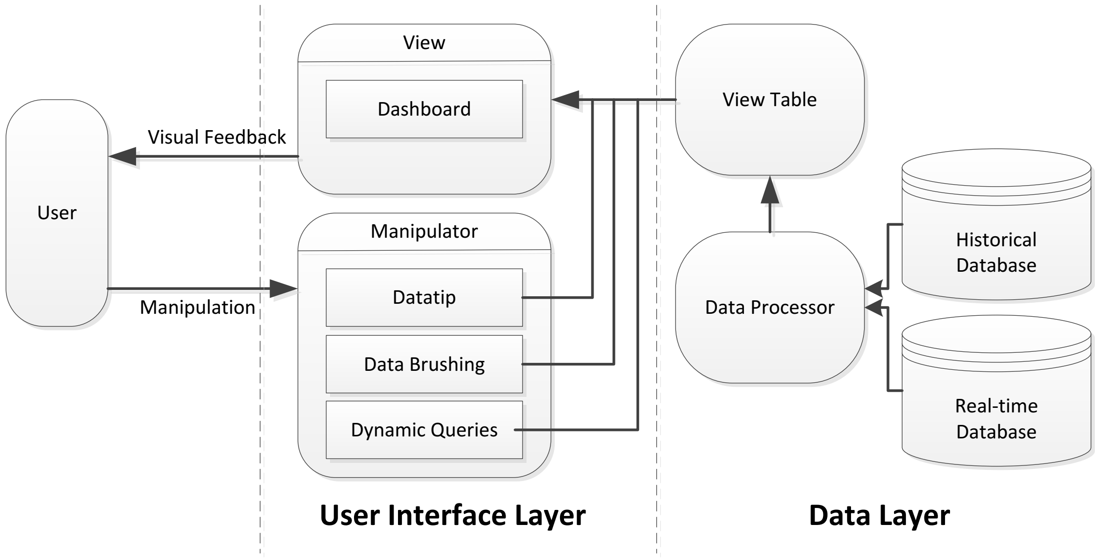


Fig. 2: The two-layer structure of the IDVS.

5.4 Displaying information in the IDVS

In the past, experts from different fields first collected the relevant data and continued monitoring the latest conditions in order to prevent human lives and property from being threatened when there is a flood potential. In this research, the IDVS is designed to display three kinds of information within a dashboard: precipitation, geographical conditions, and alert threshold. The IDVS provides an intuitively operated interface so that users can make timely decisions. Fig. 3 shows the user interface of the IDVS. The upper-left-side window (Frame A) shows the distribution of the precipitation stations that reach certain level of flood warning. The lower-left-side window (Frame C) lists the towns that already have a high level of flood potential. The center window (Frame D) displays the distribution of those towns with high flood potentials. The following paragraphs describe each display of the IDVS separately.

Precipitation: Precipitation is a critical indicator when judging flood potential. Once the 24-hour accumulated precipitation exceeds the threshold of extremely heavy rain, the experts would inform the authorities concerned about holding a meeting to discuss the set-up of a CEOC. As shown in Fig. 3 (Frame A), the circles represent the stations' rainfalls during the hourly time interval, at 8:00 pm on 12th June 2012, and the 1-, 3-, 6-, 12-, and 24-hour accumulated precipitation of each station is proportional to the radius of those circles.

Alert threshold: This research uses two different colors to represent the alert status of each precipitation station: the orange spots represent the 24-hour accumulated precipitations reaching the threshold set up by the CEOC, and the blue represents one that reaches level 1 or level 2 alert of flood warning, but has not reached the threshold of the CEOC set-up.

Geographical conditions: According to experience, the same flooding situation may occur when both the same precipitation and geographical conditions of a previous flood are satisfied. Thus, the Water Resources Agency has designated alert-affected areas based on each precipitation station's location. The dashboard in Fig. 3 shows the situation on 12th June 2012 at 8:00 pm. As shown in Fig. 3 (Frame B), we can see that there are 73 towns that reach extreme torrential rain, 350 millimeters. Fig. 3 (Frame C) lists the alert-affected towns' names in detail, and Fig. 3 (Frame D) shows the distribution of those towns. In this way, users can realize the flood potential situation with direct visual feedback. Experts may also make judgments based on the high flood potential regions. The khaki-colored belt areas in Fig. 4 (Frame A) represent the high flood potential regions in Taiwan. Hence, when the regions with flood potential (the orange areas in Fig. 4 (Frame A)) overlap with the high flood potential regions, the probability of a flood occurring is greatly increased.

5.5 Interaction functions in the IDVS

Datatips: As shown in Fig. 6, some detailed data, such as precipitations, a station's name, and the warning areas' names, are displayed in a tooltip when users place the mouse over the desired station. In the past, we had to manually match this data between different Excel sheets and then list them in a table. Thus, the use of the datatip function obviously helps users to get required information more efficiently than before.

Dashboard: As shown in Fig. 3, the use of the dashboard maximizes the performance of the IDVS. Unlike the traditional approach, which can only show those views on a static display, users can interact and compare the flood-related information simultaneously within different displays on a single screen. In some circumstances, users need to gain a deeper insight to understand the trend of rainfall over a certain time interval. Hence, we designed a function that allows the user to browse the precipitation hyetograph of a certain station. As shown in Fig. 5, the subview of dashboard is displayed when users select a circle representing a certain precipitation station in Fig. 3 (Frame A). Frame A1 highlights the station's position on a map of Taiwan, while Frame A2 highlights the bar representing the precipitation measured by the station on 12th June 2012 at 1:00 am.

Data brushing: As shown in Fig. 7, when users select an element in the lower-left-side window, other relevant elements of that selected element in other displays will be highlighted. For example, when an alert-affected town's name is selected, the source precipitations in the upper-left-side display, and the alert-affected area's location in the right-hand-side display will be highlighted. Thus, users can rapidly learn the absolute positions of those affected areas.

Dynamic queries: In this research, we designed two scroll bars for dynamic queries function. The first bar allows users to adjust the 24-hour accumulated precipitation. As shown in Fig. 3 (Frame E), when users increase the threshold of 24-hour accumulated precipitation by scrolling the slider while keep the dates and time as the same, the number of precipitation stations reaching the threshold decreases. For example, when adjusting the value from 200 to 350, users can find out that within the same date, under which threshold will have the requirements of the set-up by CEOC, as shown in Fig. 8. The other scroll bar allows users to adjust dates and times. As shown in Fig. 3 (Frame F), when dragging the slider of the scroll bar from left to right, users can browse the changes in the precipitation distribution by hour. For example, when dragging the time slider from 10th June 2012 at 3:00 pm to 12th June 2012 at 3:00 pm, users can learn that the number of warned towns rose from 5 to 25 and also see the changes of orange polygons' numbers, as shown in Fig. 8.

6. COMPARISON BETWEEN EXISTING AND IDVS PROCEDURES

We chose data from the flood beginning on 10th June 2012 (called the 610 flood) in Taiwan to implement our system. We make two comparisons between the existing procedure and the IDVS procedure. The first is to compare the information rendering approach and the second is to compare the efficiency of decision-making.

In the existing flood warnings procedure, the rendering of information has limited interaction with users so that they can only make judgments based on reading paper reports back and forth repeatedly. Moreover, the experts present their own viewpoints individually based on different sources, so that it is difficult for them to reach a consensus. The current procedure lacks an integrated platform for experts to communicate, so the procedure for making judgments to decision making takes a long time.

By using the IDVS to deal with flood warnings, users can intuitively make judgments by interacting with information in the user interface. The IDVS has integrated flood-related information so that it can improve the efficiency of communication and accelerate the procedure from making judgments to decision making.

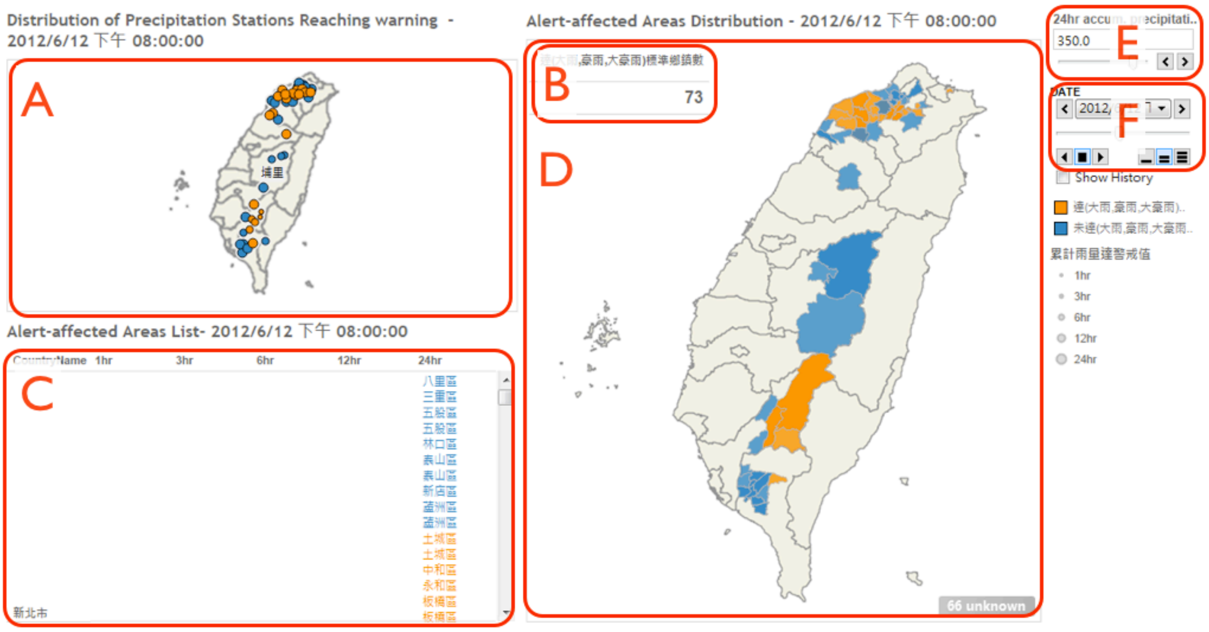


Fig. 3: Dashboard: Distribution of precipitation stations having reached level of flood warning.

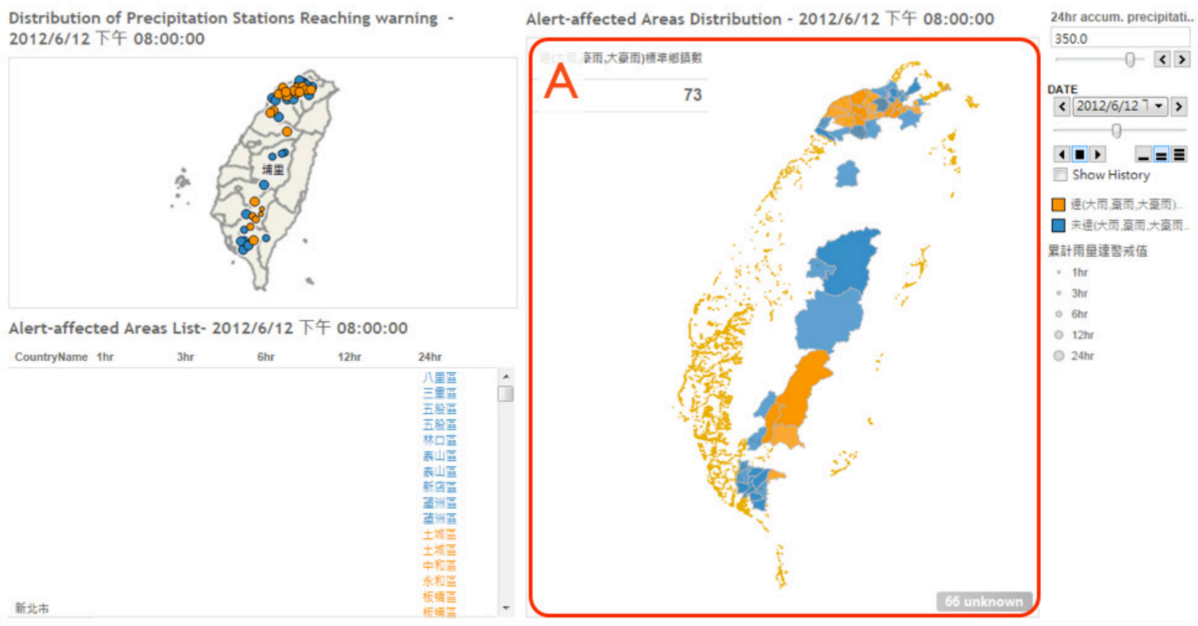


Fig. 4: Dashboard: the high flood potential regions.

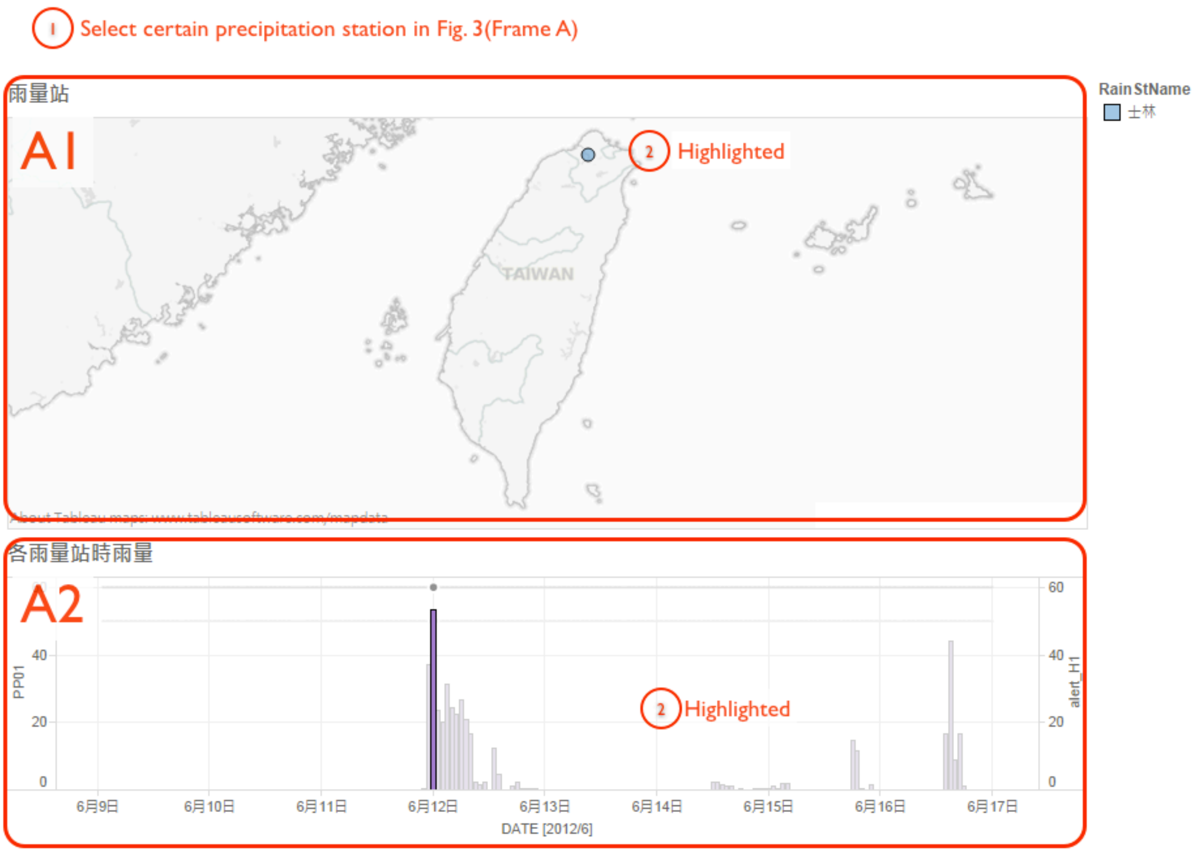


Fig. 5: Subview of the dashboard: the location and hourly precipitation hyetograph of a station.

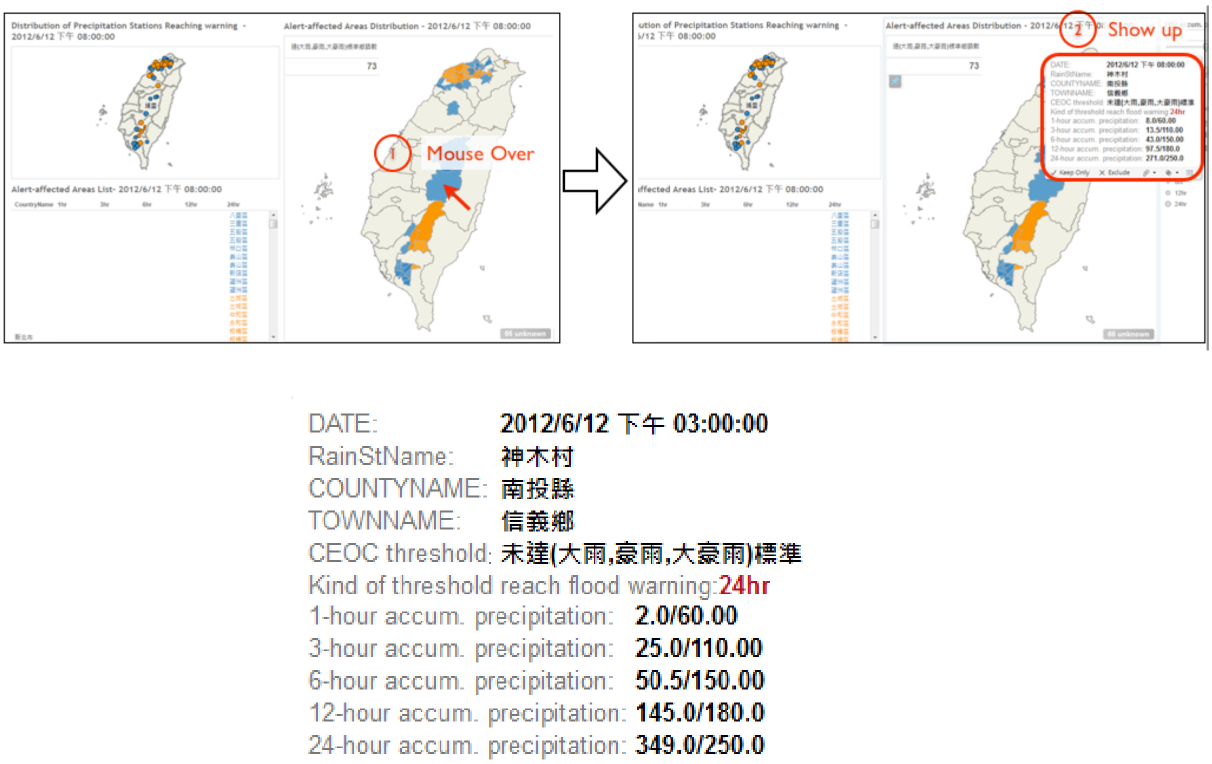


Fig. 6: (Top) The Datatip function and (bottom) datatip box

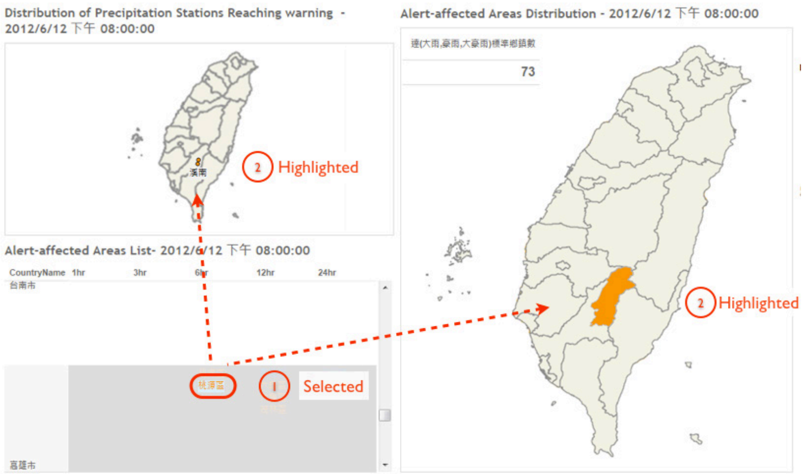


Fig. 7: The Data brushing function.

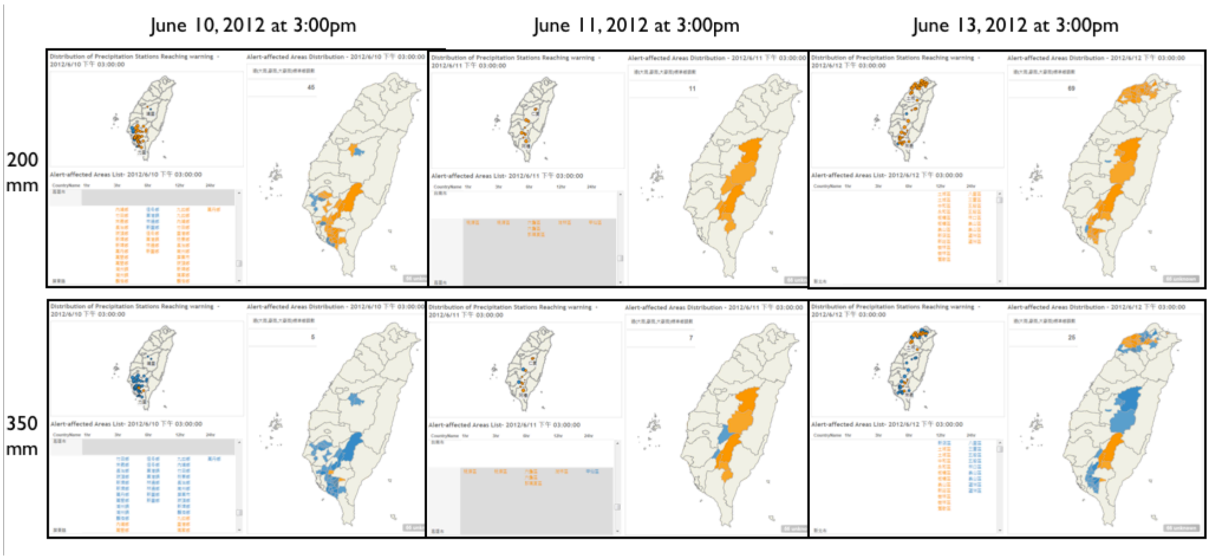


Fig. 8: The Dynamic queries function (Figure changes horizontally by changing the date, and changes vertically by changing the alert threshold.)

7. CONCLUSION AND FUTURE WORK

In this research, we develop an Interactive Data Visualization System (IDVS) for flood warnings that can help decision makers rapidly determine the potential flood areas and react with disaster mitigation plans accordingly . In the IDVS, the multi-dimensional flood-related data is collected, and each row contains property-wise information such as the 1-, 3-, 6-, 12-, 24-hour precipitation accumulations and its own alert threshold for two different levels of flood warning. Four interactive functions, Datatips, Dashboard, Data brushing, and Dynamic queries, were developed for this system, which allowed users to manipulate the critical information directly and to obtain visual feedback. Datatips display different levels of detailed information hidden behind a specific element, from different event dates, locations, to precipitations and alert thresholds, when the mouse hovers over it without losing the overall sense of clarity. By collecting both the rainfall-related and geographical information together in a single dashboard, users are able to gain deeper insight into their relationship by comparing different views and making communication more convenient than paper-based presentation. Data brushing allows users to explore the exact locations of the towns and their triggered precipitations in other displays. Dynamic queries provide two scroll bars that are able to filter the data by date and time or by the 24-hour accumulated precipitation. This research used disaster information from a flood occurring in Taiwan on 10th June 2012 to implement the system.

Thus, the proposed method can improve the efficiency of dealing with multi-dimensional information and facilitates decision making for users. As a result, by taking advantage of the IDVS, users can save time usually wasted on mapping information coming from different sources and inefficient communication with team members. In future research, we will conduct an interview with five experts by offering five practical problem–related questionnaires to see the experts' exploration of the IDVS program and their assessment. The results will show whether this system can allow users to easily comprehend and interpret disaster information.

8. ACKNOWLEDGEMENT

The authors appreciate the Water Resources Agency, Taiwan, for providing data in this paper. The authors would also like to thank Ms. Yi-Hui Chang, Mr. Shih-Kun Chuang, and Dr. Tsung-Yi Pan of Center for Weather Climate and Disaster Research, National Taiwan University for their experiences in the operating procedures for flood warnings.

9. REFERENCES

Boin A., Hart P., Stern E. and Sundelius B. (2005). *The politics of crisis management: Public leadership under pressure*, UK: Cambridge University Press.

Card S. K., Newell A. and Moran T. P. (1983). *The Psychology of Human-Computer Interaction*, New Jersey: Lawrence Erlbaum Associates, Inc..

Colin Ware. (2004). *Information Visualization: Perception for Design*, San Francisco, CA: Morgan Kaufmann Publishers Inc..

Crapo A. W., Waisel L. B., Wallace W. A. and Willemain T. R. (2000). Visualization and the process of modeling: a cognitive-theoretic view, *Proceedings of the sixth ACM SIGKDD international conference on Knowledge discovery and data mining,* Boston, Massachusetts, USA, August 20-23.

Deshons, P. (2002). Prevision et suivi des crues urbaines. *Experience de la ville de Marseille,* La Houilles Blancin, No. 2, 56-59.

Flood Forecasting Centre. (2010). *Extreme Rainfall Alert (ERA) Service User Guide*. Available from: http://www.ffc-environment-agency.metoffice.gov.uk/media/pdf/FFC_ERA_User_Guide.pdf [Accessed 23 August, 2012].

Hurford A. P., Parker D. J., Priest S. J. and Lumbroso D. M. (2012). Validating the return period of rainfall thresholds used for Extreme Rainfall Alerts by linking rainfall intensities with observed surface water flood events, *Journal of Flood Risk Management*, Vol. 5, No. 2, 134-142.

Johansson J., Neset T. S. S., Linne, X and R. B. O. (2010). Evaluating Climate Visualization: An Information Visualization Approach, *Proceedings of Information Visualisation (IV), 2010 14th International Conference*, London, July 26-27. 156-161.

Khan M. and Khan. S. (2011). Data and information visualization methods, and interactive mechanisms: A survey, *International Journal of Computer Applications*, Vol. 34, No. 1, 1-14.

Netherlands US Water Crisis Research Network (NUWCReN). (2012). *Flood Preparedness in The Netherlands: A US Perspective*, Netherlands: NUWCReN.

Shneiderman B. (1986). *Designing the user interface: strategies for effective human-computer interaction*, Boston, USA: Addison-Wesley Longman Publishing Co., Inc..

Shneiderman B. (1994). Dynamic Queries for Visual Information Seeking, *IEEE Software*, Vol. 11, No. 6, 70-77.

World Meteorological Organization (WMO). (2007). Implementation of a flash flood guidance system with global coverage. Available from: http://www.hrc-lab.org/giving/givingpdfs/WMOProspectus_April-2007.pdf [Accessed 2 May, 2011].

Thomas J. J. and Cook K. A. (2006). A visual analytics agenda, *Computer Graphics and Applications, IEEE*, Vol. 26, No. 1, 10-13.

FLOOD GAME: AN ALTERNATIVE APPROACH FOR DISASTER EDUCATION

Ming-Chang Wen, Meng-Han Tsai, Shih-Chung Kang & Yu-Lien Chang
National Taiwan University, Taiwan

ABSTRACT: *Flooding is a frequent disaster in typhoon season in Taiwan nearly every year. To prevent flooding, the decision-makers need to invest in costly constructions, such as embankments and disaster parks. They also need to carefully allocate resources, such as sand bags and pumps, to minimize the damage caused by the heavy rain during a typhoon. This paper presents an ongoing disaster education project, for disaster education for which we designed a flood game allowing high school students to play the role of the decision makers. We based the flood game on the popular "tower defense game," in which players need to allocate limited resources before and during random attacks because the decision behaviors are very similar between the decision makers of flood prevention and the players of tower defense. The flood game has two independent goals: happiness index and money. The happiness index represents the citizens' satisfaction. The money is a subtraction of the construction items from the total tax income. If the city is well protected, the tax income will increase and vice versa. The players need to wisely allocate the money to build the necessary facilities around the riverside in the right places and at the right time to maximize efficiency of the expenditure. We included six common construction items for flood prevention, including sand bags, pumps, dikes, disaster parks, green roofs, and green streets. We also developed six levels for the game, from the easiest (only one available construction item) to the most difficult (six available construction items) to help players progressively learn the game. If the city resists attacks from heavy rain successfully, the players can pass the level and proceed to the next one. To validate the use of the game, we tested the game with 148 high school students and found that it cannot only increase their interest in learning but also help students understand the complexity of flood prevention for the decision-makers. In the near future, we will develop follow-up teaching materials and videos to leverage the learning outcome after playing the game.*

KEYWORDS: *Game-Based Learning, Interactive Game, Flood Defense, Education*

1. CHALLENGES OF CURRENT DISASTER EDUCATION

Two critical challenges that need to be addressed in disaster education are student motivation and experience delivery. First, enhancing the learning motivation of students is a rising topic in research of education methods. Education methods play an important role in triggering students' learning motivation and furthering the enhancement of participation. Many studies indicate that there is a large increase in the learning motivation of students who receive the experiential education method. Experiential education is a method that involves the students in physical or virtual scenarios and makes them understand the knowledge behind the experience. During the experience, students have to look for the answer and figure out how things work all by themselves, which causes them to make more effort unconsciously. Motivation and participation are also enhanced naturally. In the field of disaster education, traditional education methods usually stress theoretical and conceptual knowledge rather than experiential ones. It is a great challenge to combine disaster education with the experiential method. The second challenge is to deliver field experience to students in the classroom. Traditional disaster education placed emphasis on the teaching methodology rather than the experience behind it. Past real world experiences indicate that many critical problems came from an inappropriate distribution of resources, and these problems usually differed in many cases based on disaster types, intensity, and geographic information, etc. Instead of teaching oversimplified experiential principles, letting students learn by doing gives them more flexibility and independent thoughts in disaster education.

Citation: Wen, M-. C., Tsai, M-. H., Kang, S-. C. & Chang, Y-. L. (2013). Flood Game: an alternative approach for disaster education. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

2. GAME-BASED LEARNING FOR DISASTER EDUCATION

Game-based learning is emerging as a hot topic in education. There has been growing interest in the potential of computer games in educational environments in recent years. The inception of educational gaming originated from the integration of computer science and operations research, associated with the issue of educational theories that stress on active, experiential learning and reflection. The first computer games with educational purposes were developed in the late 1960s after the first computer games were developed (Wolfe & Crookall, 1998). Playing games has a powerful influence on learning and it is fundamental to the development of both adults and children (Rieber, 1996), enhancing engagement and mastery with practical experience (Colarusso, 1993). Games are a fundamental part of the evolving human experience and learning method, providing the opportunity to practice and explore in a safe environment, teaching skills like aiming, timing, hunting, strategy and manipulation of resources and power (Koster, 2005). Game-based learning is an educational method that has defined learning procedures and goals according to a specific topic. It is designed to balance topic subjects with game play and requires the player to have the ability to retain and apply the given subjects to the reality. The learning would happen almost without the learners' realizing it, in pursuit of beating the game. We are encouraging them to learn by "stealth learning" (Prensky, 2001). When education or training is tedious, students are not engaged or motivated. In other words, they are not really learning. Rote memorization of traditional learning often leads to unsustainable learning outcome. Acquiring the skills and thinking processes needed to respond appropriately under pressure in a variety of situations is the great challenge of game-based learning.

In this case, we chose flooding as the topic of disaster education. Worldwide flooding has been brought to our attention by the media in recent years. Not just in Taiwan but also in other countries such as the United Kingdom (Lin Chen, 2013). Regardless of the time and location, flooding always brings a host of challenges to settlements and leaves both short-term and long-term impacts; the impacts are seldom beneficial, which is why it is crucial for students to understand the basics of flood protection. A game-based learning method in flood defense education should be developed since the lack of interaction between students and knowledge is a critical defect of the current flood defense education.

3. GAME DESIGN

We expect a game to enhance the learning motivation of students through learning by doing. This paper aims to develop a tower-defense-like computer game for disaster education. Game players need to defend multiple areas, which may be residential, commercial, or industrial areas in a city, and prevent those areas from waves of floods by using a variety of items representing different engineering approaches. They need to place appropriate construction items to prevent the city from flooding. The key to victory depends on how well the player manipulates the resources. Special policies can increase the items' effectiveness in specific regions. After a certain number of waves, the total score will be evaluated depending on designed indices.

Direct instruction is minimized to encourage students' active learning by exploration (Mitchel, 1998). Students play the role of decision makers (ex. mayor) of a city which suffers from flooding. They will learn different basic engineering methods and concepts regarding flood prevention throughout the game. The main purposes are to let students understand how to manipulate existing engineering approaches and resources to combat flooding before and after it occurs, and to instill knowledge regarding modern water conservation methods and policies in students. By experiencing the game, students not only acquire the knowledge they would not normally learn in traditional disaster education but they are also prompted to look at the bigger picture of this issue (Klopfer & Osterweil & Salen, 2009).

4. GAME CHARACTERISTICS

In order to answer the question of what makes a computer application enjoyable to operate, Malone (1980) proposed three essential characteristics: challenge, fantasy, and curiosity. In this game, challenge and curiosity are our main concerns; fantasy is not relevant to games that need to connect the experience to reality (Ebner & Holzinger, 2007). We therefore developed the design principles by implementing the challenge and curiosity elements.

4.1 Challenge

Design principles must encompass a predefined goal and allow the provision of performance feedback regarding the players' imminence to achieving their goal. The achievement rewards must be unpredictable. The gaming difficulty should be adjustable in this respect and a score calculation is needed for comparison.

4.2 Curiosity

Activities designed to trigger the players' curiosity must provide an optimal level of informational complexity (Piaget, 1951). This includes adding variety at random without making the tools unreliable. Game environments should be neither too complicated nor too simple with respect to the end-users' existing knowledge (Malone, 1980). During game play, the game must be novel and surprising while remaining comprehensible. An optimally complex environment will be one where the players knows enough to be able to anticipate what will happen but where their expectations are sometimes wrong.

5. GAME FEATURES

We defined four major features of the game. Each of them is an independent function but has shared variables and mutual influences. Every decision the player makes triggers a series of changes to the indices and scenario.

5.1 Multiple protection regions

The game includes three protection regions: residential, commercial, and industrial. Each region has its own properties such as population, tax rates, and resistance to floods. The residential region is where most of the population lives but generates the least amount of tax income. Contrastingly, the commercial region has the lowest population and the highest tax income among the three. In the industrial region, both the population and tax rates are of a moderate level. These designs simplify the reality reasonably while maintaining the balance of the game without involving complicated political issues.

5.2 Multiple evaluation indices

We defined two main indices for the evaluation of a single game play; happiness index (HI) and money. HI represents the satisfaction of the residents. As a decision maker, people's satisfaction is the main concern. The HI is designed to drop if any region suffers from flooding. Players will fail the game once the HI becomes 0. After the end of the final wave of a flood attack, the HI is one of the main references for the total score. Money resources are another important issue in disaster mitigation. In this game, money comes from the tax income of the three regions periodically. Different regions pay a certain amount of money according to the tax rates. Players can use money to buy flood prevention products, remedial measures, and infrastructure in this game. Players have to balance the HI and money while manipulating the arrangement of the different flood protection approaches.

5.3 Multiple approaches for disaster mitigation

Players can make use of multiple approaches for disaster mitigation to defend the shores from flooding. We want to design construction approaches and policies, each of which has their own properties of cost, durability, and efficiency. The design of the construction approaches are based on two types of approach for the decision maker, namely positive and passive approaches. A positive approach usually costs more but is efficient and guarantees sustained protection such as dikes and retention parks. Players have to save resources for positive approaches, meaning they have to give further consideration to pre-construction activities. Passive approaches are much more affordable compared to positive ones but the limited durability is unavoidable. Players use passive approaches as temporary and emergency approaches, such as sand bags and pumps, which are not the solution for a long-term flood protection plan. Another classification is the actual method of flood protection. We simplify and merge multiple methods into two categories: blockage and drainage. Blockage methods keep overflow water in the river by hard blocking. Drainage methods distribute the outflow of water to reduce the loading of the river. Since we have two categories and two different approaches, four different approaches are generated: sand bags, pumps, dikes, and retention parks. (Table 1)

Table 1: Classification of construction approaches

	Positive	Passive
Blockage	Dike	Sand Bag
Drainage	Retention Park	Pump

a. Sand Bag: Sand bags can be placed on the corners of a river to mitigate water overflow from flooding. Nevertheless, sand bags will be damaged over time and eventually destroyed by the impact of flood waves.

b. Pump: Pumps can extract a fixed amount of water from the river in a certain period but do not last forever. This is designed to reflect the fact that it is not a long-term solution.

c. Dike: Dikes function in the same way as sand bags, with the only difference being that dikes will not be destroyed by the sustained impact of flooding.

d. Retention Park: A retention park can distribute water continuously and has no limited lifespan. It also provides entertainment for residents whose satisfaction affects the HI.

Additional policies are designed as advanced approaches for a player to enhance a specific region's durability against floods. After reviewing current mitigation policies, we selected two policies for our game: green roofs and streets:

e. Green Roof: This policy can be applied to a specific region to increase its ability to store water. The durability of construction approaches around the region upgrades once this policy is conducted.

f. Green Street: This policy can be applied to a specific region to gain more storage for overflow water. With this policy, the region is able to absorb overflow from the surrounding rivers.

5.4 Sequential levels with increasing difficulty

Six levels are designed with different maps and difficulty levels. Each map has a unique river course and region distribution. With the increasing difficulty levels, flood-prone areas become harder to protect. It forces players to consider different strategies for manipulating the resources and the different approaches. Another challenge is that we reveal a new approach or policy in each level. Players get an additional more efficient approach in every level, that is, they have one approach in level 1, two in level 2, etc. In the last level, level 6, all approaches and policies are unlocked for players to use. This setup allows them to have more choice in the decision making process.

6. GAME DEVELOPMENT

We designed the game with the principles and desiring features mentioned above. First, we made an experimental cardboard game as a prototype (Fig. 1) of our computer game to define the game's functions and rules. It was easier for inspection and revision purposes before actually initiating computer software development. Second, after all major revisions were confirmed, we started programming the whole structure of the game on Adobe Flash CS6 platform using its language, Action Script 3. Third, we focused on the numerical setup and calculations such as the relation of indices, item prices, and timing, which have a great influence on user experience and game balance.

6.1 Prototyping

A cardboard game is an efficient method for the early stages of game development. It provides designers, artists, and programmers a handy and visual tool for thorough discussion. By playing step-by-step with cardboard, designers can discover and refine unexpected procedures, rule bugs, and gaming experience.

6.2 Implementation

The flood game was programmed and designed with Adobe Flash CS6 after detailed refinement with a cardboard game prototype. Flash is one of the primary tools for creating content for interactive software. The programming language Action Script 3 makes it possible to program end-user-dependent interactive and specially designed games. One main advantage of using Flash is the very compact file size that is a precondition for usable distribution. Furthermore, browser plugins are usually preinstalled in popular web browsers, which maximize the compatibility. We preferred Flash because of the possibility to quickly develop a usable and visualized game prototype.

Before programming the main game play, we first drew a skeleton of the desired game flow (Fig. 2) and linked each function. It presents a full cycle from starting the game, choosing the level, and the main game play, to showing the results. The players' entry interface is the *game main menu,* which includes three choices, *play*, *option*, and *help*. *Play* allows players to select a level and play the game. In the game play, we also designed a pause menu allowing players to restart, quit, and go to the *option* function. Every game play ends up with either success or failure as typical gaming feedback. A scoreboard showing players' gaming results appears if players succeed rather than fail in the game. The interface then goes back to the game main menu to start a new game. O*ption* has a switch allowing players to turn the sound effects on and off. H*elp* has several gaming tips for players to explore to see how the game reflects flood protection in the real world.

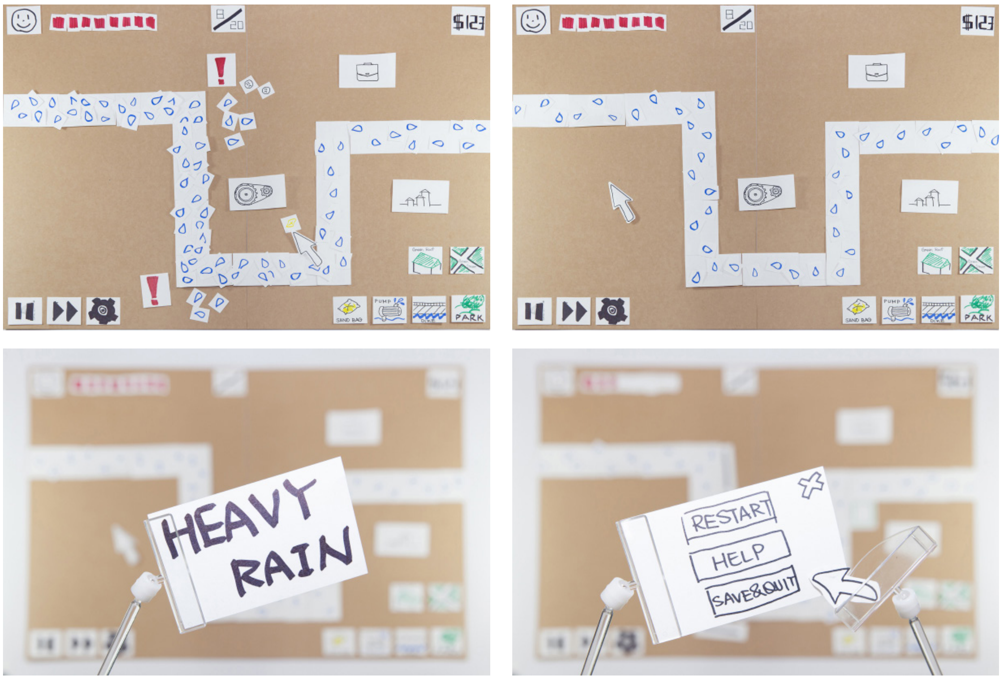


Fig. 1: Cardboard flood game prototype

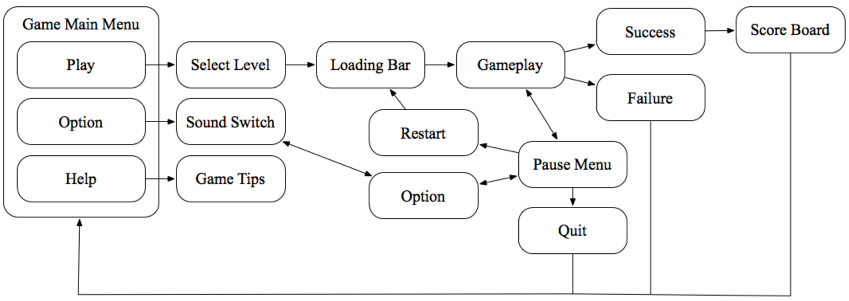


Fig. 2: Game flow skeleton

Next, we developed the main game play with the general gaming setup (Table 2.). This table simply explains the coding relationship between the major variables. Two parts, initial and conditional setups, are sectored according to whether the specific function needed to be updated in real-time. For example, in initial setup, money was initiated with a predefined value of 0, which is assigned a one-time variable (Table 2. (2)). However, in the conditional setup, money increases by collecting taxes from regions with values 3, 5, or 10 for every 3 seconds that pass (Table 2. (16)). Once all functions were programmed, we started to tune the numerical data used in functions to make the game more playable. These values provide a unique difficulty for the game. To improve usability, we created three tables (Table 3, 4, 5.) to show the customization of difficulty levels. The tables include numerical data for flood-prone regions, construction approaches, and policy approaches. We carried out the user test using values in the tables which provided a medium difficulty gaming experience for Taiwan high school students.

The final refinement of the software was to make the game look attractive. Our artists illustrated the six cities with a river passing through, the three regions with buildings, the construction and policy approaches, and every button and icon was designed in the same style. The unified graphic design style made the game look appealing for our target user, high school students. The game was then functional and ready for further user tests after replacing all temporary interface illustrations with the artists' designs (Fig. 3).

Table 2: General gaming setup

Type	Variable	Function	Relative Variables
Initial setup	HI	(1) HI is initiated with 500 units.	--
	Money	(2) Money is initiated with 0 units.	--
	Wave	(3) 5 waves of flood in every level.	--
	Wave	(4) 45 seconds lifespan for each wave.	--
	Water units	(5) Every water unit has a level property indicating its volume.	--
	Riverside spots	(6) Every riverside spot can endure a water unit of level 1.	--
	Riverside spots	(7) Every spot allows player to build 1 construction approach.	--
Condition setup	Water units	(8) Wave difficulty gradually increases with higher level of water units.	Wave
	Overflow units	(9) Water unit level beyond 1 will make an extra overflow unit.	Water units
	Overflow units	(10) 1 level higher, 1 more overflow unit is made.(ex. 3 overflow units are made by water unit level 4.)	Water units
	Overflow units	(11) Overflow unit counteracts 1 overflow durability of a construction approach.	Overflow durability
	Overflow durability	(12) Construction approach's overflow durability is predefined; it reduces after encounter overflow units.	Overflow units
	HI	(13) If overflow units hit a spot that have no construction approach, it means the specific region is attacked which causes a drop in HI.	Overflow units
	HI	(14) 5, 2, 1 HI drops when suffer from 1 overflow unit in residential, industrial, commercial region correspondingly.	Overflow units
	HI	(15) If there are no overflow unit hits for 10 seconds, residential, industrial, and commercial regions self-recover 3, 2, 1 HI every 6 seconds.	Overflow units, Time
	Money	(16) Residential, industrial, commercial regions pay 3, 5, 10 units of taxes every 3 seconds.	Time
	Result	(17) Pass all 5 waves without losing all HI to win.	HI, Wave
	Result	(18) Lose all HI means failure.	HI

Table 3: Flood-prone regions' numerical data setup

	Residential	Industrial	Commercial
Tax income per 3 seconds (money)	3	5	10
HI self-recovery per 6 seconds (HI)	3	2	1
HI drop per overflow unit hits (HI)	5	2	1
Overflow durability (overflow unit)	250	150	200
Satisfaction of residents (HI raised every 3 seconds)	0	1	5

Table 4: Construction approaches' numerical data setup

	Sand bag	Pump	Dike	Retention Park
Cost (money)	5	10	50	100
Overflow durability (overflow unit)	10	20	Infinity	Infinity
Satisfaction of residents (HI raised per 3 seconds)	0	1	2	5

Table 5: Policy approaches' numerical data setup

	Green Roof	Green Street
Cost (money)	150	150
Function	Upgrade surrounding constructions	Enhance the durability of region against overflow
Effect (per time)	- Extra durability for Sand Bag (+2) and Pump (+2). - Extra HI for Sand Bag (+1), Pump (+1), Dike (+2), and Retention Park (+2).	- 1 more overflow unit durability for all riverside spots around applied region.

Fig. 3: Flash flood game screenshots

7. FIELD TEST

We hosted two activities for high school students in Taiwan. Sixty-two high school students from different cities in Taiwan participated in a civil engineering camp hosted on January 24, 2013 (Fig. 4a). It was the first time that we introduced our flood game in public. We gained a substantial amount of user test data through observing their responses during game play. After analyzing these data, we found that we still needed more samples to resolve a precise validation. Therefore, we started planning for another activity which was held on February 5, 2013 in Hu-Wei high school, Yunlin County, Taiwan (Fig. 4b). Seventy-nine students and seven teachers participated. Furthermore, we also received many practical suggestions from a local professional flood mitigation team.

Fig. 4: (a) Civil engineering camp and (b) Hu-Wei high school camp

In each activity, we offered twelve desktop computers and divided participated students to played in groups of

three. The computer screen, mouse tracks and also students' voices and facial expressions were recorded during the gameplay. We also recorded the audio and video of the discussion and self-directed learning session. Two observers were assigned to each group to monitor their behavior during playing the game. The observers wrote down all notable discussion, emotional and motivation feedbacks. After these two activities, we sorted the collected data and summed up some ideas. The flood game generally raised students' learning motivation. Students liked to learn with the interactive game comparing with traditional lectures in which motivation is hard to maintain. Therefore, it is necessary to create game-based learning solutions that combine the attributes of motivating the students with designed software, which is joyful and does not feel like traditional learning. This idea was the incentive for the development of the flood game that was designed for disaster education.

8. RESULTS AND CONCLUSION

We conducted detailed behavior analysis by using the recorded video and observers' notes. We conclude that the flood game is an effective material in flood protection education. All the collected data are sorted into the four act indices: discussion, question, laughter, and screaming. These are valuable references for the motivators of hope and pleasure. Furthermore, we use the four status approaches (explore, aware, fluent, known), which can be used to evaluate the players' ability in the game; the observation of learning experience shows that students asked related questions and found strategies to fight against the floods. The flood game generally raised students' learning motivation. Students liked to learn with the interactive game comparing with traditional lectures in which motivation is hard to maintain. Students who have low motivation and high ability in a traditional learning environment were triggered after playing the game. The game-based learning in disaster education is a successful persuasive design. It has successfully enhanced students' motivation to learn more about flooding. The game does benefit disaster education, thus it indicates that an interactive game may promote students' motivation in disaster education and caused behavior change. Therefore, it is necessary to create game-based learning solutions that combine the attributes of motivating the students with designed software, which is joyful and does not feel like traditional learning. This idea was the incentive for the development of the flood game that was designed for disaster education. Further results will be organized and presented in future publication.

9. ACKNOWLEDGEMENTS

This research is supported by Taiwan's National Science Council (NSC) under contract 101-2515-S-002-002. The authors are grateful to the project's contributors from National Taiwan University: Sarah Chen Lin, Kai-Lin Kao, You-Rong Kuo, Pei-Yen Liao, Ting-Ju Chen, Da-Yio Tseng, Chih-Tian Shih, Yi-Zhi Tsai, Ting-Ying Chang Jian and Ting-Ju Chen. The authors further thank our project reviewers Ko-Chiu Wu from the National Taipei University of Technology, Jing-Yuin You from National Taiwan University, Chang-E Zhou from the Taiwan Institute of Economic Research, Yu-Chen Lin from National Taiwan University, and Xi-Ting Fang from the Center for Weather Climate and Disaster Research for guiding the students and reviewing the educational methods.

10. REFERENCES

Colarusso, C. A. (1993). *Play in adulthood*. Psychoanalytic Study of the Child, 48, 225–245.

Ebner, M. & Holzinger, A. (2007). *Successful implementation of user-centered game based learning in higher education: an example from civil engineering*. Computers and Education, 49(3), 873–890.

Klopfer, E., Osterweil, S., Salen, K. (2009) *Moving learning games forward: obstacles, opportunities and openness*. The Education Arcade, MIT.

Koster, R. (2005). *A Theory of Fun for Game Design*. Scottsdale, Arizona: Paragylph Press.

Lin Chen, S., Tsai, M.H., Chang, Y.L. and Kang, S.C. (2013). *Game-Initiated Learning: A Case Study For Disaster Education Research In Taiwan*. Proceedings of AAAI 2013 Spring Symposium Series: Designing Triggers for Behavior Change, Stanford, California, March 25-27, 2013.

Lin Chen, S., Tsai, M.H., Kang, S.C. and Lai J.S. (2013). *Prototyping Interactive Games for Water and Disaster Education*. Proceedings of AAAI 2013 Spring Symposium Series: Designing Triggers for Behavior Change, Stanford, California, March 25-27, 2013.

Malone, T. W. (1980). *What makes things fun to learn? Heuristics for designing instructional computer games.* Proceedings of 3rd ACM SIGSMALL symposium and the first SIGPC symposium on Small systems, 162-169.

Mitchel, R. (1998). *Technologies for lifelong kindergarten*. Published in Educational Technology Research & Development, vol. 46, no. 4.

Piaget, J. (1951). *Play, dreams, and imitation in childhood*. New York, Norton.

Prensky, M. (2001). *Digital Game-Based Learning*. New York: McGraw Hill.

Rieber, L. P. (1996). *Seriously considering play: Designing interactive learning environments based on the blending of microworlds, simulations, and games.* Educational Technology Research and Development, 44(2), 43-48.

Wolfe, J., & Crookall, D. (1998). *Developing a Scientific Knowledge of Simulation/Gaming.* Simulation & Gaming, 29(1), 7-19.

THE INFORMATION SEEKING NAVIGATION INTERFACE WITH SPATIAL ICONS FOR CHILDREN

Ko-Chiu Wu, Yun-Meng Tang, Hung-Chun Chen, Chia-Jung Lin & Yi-Hsian Lee
National Taipei University of Technology, Taiwan

ABSTRACT: *This study is to develop an Information Seeking Navigation Interface with Spatial Icons for children. Designing a way-finder in Human–computer Interaction (HCI) will make seeking information easier for children. Developing a spatial icon-seeking interface can assist children as they explore digital learning. It is for this reason that we designed a new user interface in 3D which assists the human user in seeking information through the way-finder. The original idea of this study arose from the fact that humans have different spatial abilities, and that means humans should benefit from using a mental map before searching for information on the Web. Children have limited information-searching skills and exhibit different information seeking behavioural patterns through different media-type interfaces. The field testing part of this study was done at Taiwan's National Library of Public Information using its resource database.*

Taking into account the varying spatial abilities in children, this study uses three research impact factors: (1) Spatial Visualization; (2) Associative Memory; and (3) Spatial Memory. With a focus on these three factors, the recording of the experiment data, which was taken from elementary school students ageing from 7 to 11 years old, was conducted. The goal of this study is to assist children in building a mental map from this user interface.

Through usability testing and statistical analysis, we not only can better understand the way children use the spatial iconography seeking interface, but also the underlying cognitive theory, and find out how the way finding behaviour emerges. The spatial information search system can be used as an information base to improve the development of the spatial Interface design.

KEYWORDS: *Information seeking habits of children, child spatial cognition, HCI*

1. INTRODUCTION

Children have difficulty seeking information on the Web, because of their underdeveloped motor skills, difficulties with spelling, as well as their trouble understanding hierarchies, classification schemes, and metadata. The concepts of different search engine interfaces for children include designs with a variety of iconography, metadata, and hierarchies. These designs, such as Boolean Identification and hierarchical memory, aim to cater to the varying abilities of children in order to assist them in their search for information on the Web (Martens, 2012).

This study presents a Virtual Reality (VR) interface to help children search for information on the Web, by engaging the child's cognition ability and creating a three-dimensional experience. Based on the characteristics of the intuitive operation and visual preferences of young children, concepts of way-finding, information visualization and linkage of digital databases were explored in order to create a game-like interface for children searching for information. However, since children possess different kinds of spatial abilities, these varying spatial abilities influence their way-finding strategies and how they search for correct information in the VR interface.

2. CONCEPT AND MODEL

2.1 Information Behavior of the Child

Hutchinson et al. (2007) explained that many interface designs for children are in fact unsuitable for the average child's skill limitations and cognition preferences. Children can use Boolean queries in a category browser, but they have to focus on the assigned topics to navigate Web sites sequentially, in a top-down hierarchy and branching structure. This searching information mode is too complex process for children to grasp without difficulty. As a result, Hutchinson et al. (2007) recommended a plane, multifunctional interface design that

Citation: Wu, K-. C., Tang, Y-. M., Chen, H-. C., Lin C-. J. & Lee, Y-. H. (2013). The information seeking navigation interface with spatial icons for children. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

would help children search and browse for information on the Web.

Hutchinson et al. (2007) designed the International Children's Digital Library (ICDL), and applied many concepts, such as age, color, story role, award record, and book type to help children easily search for digital books. The core idea of the ICDL interface design was to combine queries of metadata interpretations. Wu (2012) suggested to have information nodes arranged in an extended 2D VR interface for digital databases so that children may search for information in a less-hyperlink intensive, less memory burdening environment. The effect of children using the 2D VR interface was better than that of the text-line interface of the National Public Library of Information in Taiwan. However, there is still an opportunity to explore the information seeking behaviour of children in this VR interface, which extends the interface from 2D into a 3D virtual environment.

2.2 Path finding Strategy and Mental Map

Downs and Stea (1973) noted that a pathfinder, in the route searching process, instead of just taking into account the distance between its present location and destination in a single route searching operation, it will take into account the changes in its surrounding environment and resulting mental thought process will result in a revision of the searching strategy.

Passini (1995) identified the three mental operations of the way-finding process as obtaining information, processing information, and correcting behaviour. These operations combine with the linear tree-hierarchy concept to define the way-finding mental map.

Spence (1999) noted that the navigation cognition includes browsing, formation of the model, interpretation of the model, and formation of the browsing strategy. Chase and Chi (1985) suggested that the way-finding process requires spatial knowledge (a mental map), which consists of two categories: route spatial knowledge and survey spatial knowledge. Route spatial knowledge was defined as a subject's ability to execute a mission with correct event order, as well as the memory recalled as knowledge needed for the event's execution. Survey spatial knowledge was defined as a subject's organizing activities for the event's execution, and the subject's mental cognition of the whole network frame in a task. The survey-oriented subject executed a way-finding mission with strategies based in a cartesian-coordinate setting, while the route-oriented subject executed one based in a relation-coordinate setting (Lawton, 1994, 1996; Cooper, 1976; Janzen, Kitchin,1997；Chang, 2008；Schade, & Herrmann, 2001).

Lawton (1996) suggested that the two kinds of way-finding knowledge, spatial location and the searching strategy, are not entirely independent of each other. One possible reason could be that the individual subject was not solely reliant on a single form of way-finding knowledge, but switched between two forms of knowledge according to the actual situation or needs of the subject (Kyllonen, Lohman,&Woltz,1984). Sadeghian, Kantardzic, Lozitskiy, & Sheta, (2006) pointed out that way-finders, even with overview support, still search based on their route knowledge.

Diverting from the way-finding idea, Kim (1999) in his information seeking study, suggested to combine the topological structures of the hyperlink and the navigation-aided concepts in order to improve the disorienting nature of the interface design. Richard Anderson (2002) argued an information schema should include a structure concept and navigation concept in order to design a system that matches the content with the human-computer interaction.

Therefore, the order of doing things (routing strategy-hierarchy) and organizational ability (mental map-network) affect the way-finder's behaviour. Although the subject may apply the survey spatial knowledge to deal with many functional units in a jumping and non-linear operating manner, too many functional units also contribute to an information overload condition. While the subjects can easily apply the route spatial knowledge approach to navigate the web, with its simple functions and lower information load, they may face breakdown problems with its incomplete informational structure.

2.3 Spatial Capacity – Child Sample Ability Definition

A child's exploratory behaviour using the VR interface to find desired information will be influenced by his or her survey and route spatial knowledge, as well as his or her ability to apply the knowledge. Garden, Cornoldi, and Logie (2002) suggested that the basic cognitive load for way-finding is not working memory, but a special kind of memory, known as Virtual-Spatial Working Memory (VSWM).

Spatial capability refers to a person's ability to produce, retain, extract and transform a visual image into a functional format (Lohman, 1988). Spatial capability is not an isolated skill, but includes a number of factors (Linn & Peterson, 1985; McGee, 1979). McGee (1979) suggested that spatial capability includes two major components: spatial visualization and spatial orientation. Carroll (1993) suggested five factors influencing spatial capability, namely, space imagination, spatial relation, vision-spatial perceptual speed, closure speed, and closure flexibility.

Miyake, Friedman, Rettinger, Shah and Hegatry (2001) developed a way to measure spatial capability. They took into consideration the research of Carrol and used the three most frequently cited factors – spatial imagination, spatial association, and speed of visual-spatial perception – as the indicators of spatial capability.

S.J. Westerman (2005) suggested that cognitive ability influences how a spatial interface is used and made reference to the cognition scale developed by Ekstrom et al. (1976). The spatial visualization, the spatial memory, and the associative memory for graphics were set as the measurement scales. Spatial visualization (VZ) tests, include the VZ-Form Board Test, VZ-Paper Folding Test, and VZ-Surface Development Test. Spatial memory (MV) tests include the MV-Building Memory Test, MV-Map Memory Test, and MV-Shape Memory Test. Associative memory (MA) tests includes the MA-First & Last Name Test, MA-Object-Number Test, and MA-Picture-Number Test.

However, when a child subject operates a VR interface to seek information, he or she does not need to engage in physical movement and has no hyposthenia limitation. Thus, the research model was set by applying the VZ, MV, and MA scales to measure the child’s reactions in the VR interface as he or she searched for information. The VZ scale was used to measure the child’s cognition speed; the MV scale was used to measure the child’s mental map and ability in location repositioning. The MA scale was used to measure the child’s memory of icons (information nodes) and the associated recognition of the digital database. Thus, the child’s interaction with the different VR interfaces, their mental mapping abilities, and information seeking behaviour can be measured by this investigation as outlined in Figure 1 below.

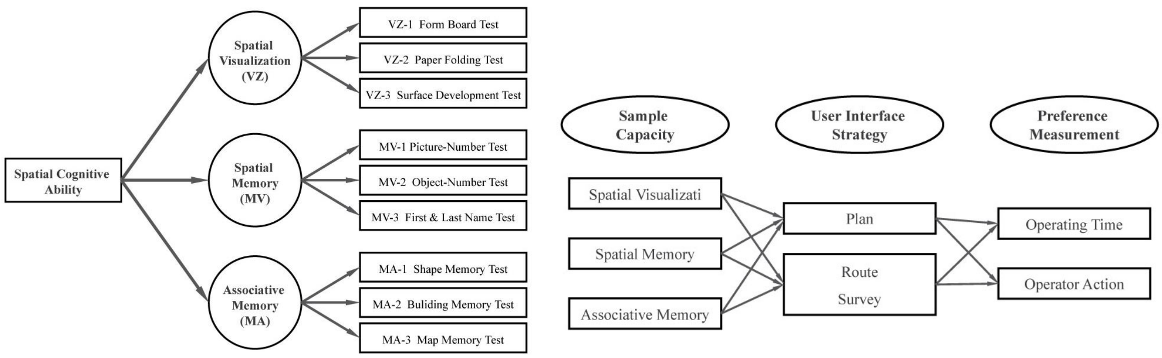


Fig. 1: Spatial ability factors and the use of measurement tools.

3. METHOD

3.1 ANOVA Analysis

The measurement groupings were put in place to distinguish between the differences in spatial abilities of the student subjects. How well they were able to replicate pictures is an example of one such spatial ability that was taken into consideration. An ANOVA (or independent sample T-test) was used to detect if the subjects with their different levels of spatial ability behaved differently as they operated the three different interfaces. This user behaviour was measured for its performance efficiency and effectiveness. Performance Efficiency measured the time used by the subject student to operate the interface and retrieve the information they sought from the database. Effectiveness measured the amount of movement, rotating and mouse clicks that was required to the retrieve information in a ratio with the total amount of those actions that took place (See Table 1).

$$F = \frac{2}{\frac{1}{r} + \frac{1}{p}}$$

The formula is defined as follows:

Effectiveness (EFT) was assessed using an F statistic (harmonic mean) that incorporates variables for recall and precision, where r = recall and p = precision.

Table 1: Interface strategies using the performance parameter design

Time Taken	Time (seconds) spent in the retrieval process per single task
Distance Traveled	In the process of adding ‘noise’ to create 80% and 60% solutions, some unwanted variation in average inter-document distance was introduced. Therefore, measures of distance travelled were scaled by an appropriate value.
Amount of Rotations	A special feature of the virtual reality spatial environment. Calculated the number of times when the right button of the mouse was clicked by the user to make a rotation.
Total Number of Nodes Visited	Recorded the total number of right or wrong mouse clicks (nodes).
Number of Different Nodes Visited	Recorded the total number of times the wrong number was clicked (node errors).
Lost State	The ratio of the number of nodes visited to the number of unique nodes visited.
Recall	Number of relevant documents retrieved expressed as a proportion of the total number of relevant documents.
Precision	Ratio of relevant documents retrieved to irrelevant documents retrieved.
Effectiveness	Effectiveness (EFT) was assessed using an F statistic (harmonic mean) that combines recall and precision: where r = recall and p = precision.
Performance Efficiency	Performance efficiency (EFY) was assessed by the ratio of (EFT) to time taken.
Self-report	Self-report workload.

Using information from the data about the cognitive ability scale of children, which is an internal factor and navigation design and way-finding, which are external factors, the questionnaire scale design was designed. In this study, a number of definitions were made. Table 2 lists the impact factors of the experiment. There were a total of three search interfaces used. One of them was a navigation-strategy interface: 'GUI-Hyperlink (GH Interface)'. The other two were way-finding strategy interfaces: 'Extended-Survey (the ES interface)' and ‘Extended Route (ER interface)'.

Table 2: The search interface nouns classification relational tables

Type	Search interface	Abbreviation	Factor	Interface	Tactics
Graphic User Interface	GUI-Hyperlink	GH	Usability	Navigation	Hyperlink
Spatial User Interface	Extended-Survey	ES	Efficiency	Way finding	Survey
	Extended-Route	ER			Route

In accordance with the data and literature outlining the research issues and impact factors, as shown in Figure 2, the first part of the experimental design was to use a 'flat-image' search interface and a 'spatial-image' search interface in order to do a comparative analysis. This first part also included the spatial interfaces of two different way-finding strategy designs; the second part, which is related to the internal factor of cognitive ability, was to find and understand the cognitive factors that affect the way children use a graphical search interface when way-finding.

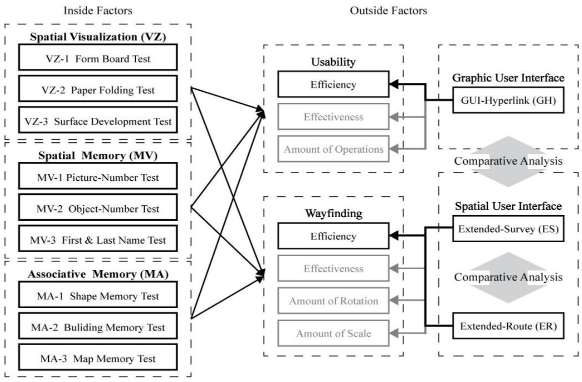


Fig. 2: Structure of Related Factors

3.2 Factor Assumptions

See Table 3 below for the list of experimental design factor assumptions.

Table 3: The factor assumptions of this study.

H1	When children search for information, there is a difference in the efficiency level between those using plane (GH) and spatial (ES, ER) interfaces.
H2	When children search for information, there is a difference in the effectiveness level between those using plane (GH) and spatial (ES, ER) interfaces.
H3	When children search for information, there is a difference in the amount of operations performed between those using plane (GH) and spatial (ES, ER) interfaces.
H4	When children search for information, there is a difference in the amount of operations performed between those using the two kinds of spatial (ES, ER) interfaces.
H5	A child's search efficency when using the plane (GH) and space (ES, ER) interfaces is affected by his or her spatial visualization ability (VZ-1 and VZ-3).
H6	A child's search efficency when using the plane (GH) and space (ES, ER) interfaces is affected by his or her associative memory capacity (MA-1 to MA-3).
H7	A child's search efficency when using the plane (GH) and space (ES, ER) interfaces is affected by his or her spatial memory ability (MV-1 to the MV-3).
H8	A child's search effectiveness when using the plane (GH) and space (ES, ER) interfaces is affected by his or her spatial visualization ability (VZ-1 and VZ-3).
H9	A child's search effectiveness when using the plane (GH) and space (ES, ER) interfaces is affected by his or her associative memory capacity (MA-1 to MA-3).
H10	A child's search effectiveness when using the plane (GH) and space (ES, ER) interfaces is affected by his or her spatial memory capacity (MV-1 to the MV-3).
H11	With children of different spatial visualization abilities (VZ-1 and VZ-3), the efficiency of the use of the plane (GH) and space (ES, ER) interfaces varies.
H12	With children of different associative memory capacities (MA-1 to MA-3), the efficiency of the use of the plane (GH) and space (ES, ER) interfaces varies.
H13	With children of different spatial memory abilities (MV-1 to the MV-3), the efficiency of the use of the plane (GH) and space (ES, ER) interfaces varies.

3.3 Information on the Study Samples

This study involved a sample of 281 subjects, 255 of whom returned valid results – a recovery rate of 91%. As shown in table 4, there were a total of 12 test groups and the subjects were second to fifth grade elementary school students who had an age distribution between 7 and 11 years old. The students were from Zhongzheng Elementary School in New Taipei City, Wanxing Elementary School in Taipei City, and Wenchang Elementary School in Taipei City.

Table 4: Subject distribution according to grade:

Grades	Classes	Number of Classes	Percentage
Second Grade	2	46	18%
Third Grade	3	65	25%
Fourth Grade	3	67	26%
Fifth Grade	4	77	30%
Total	12	255	

The subjects were divided into three groups, each using only one of the three search interfaces. This was done in order to avoid having a learning effect that would influence the performance of the subjects. The number of subjects using each interface and the corresponding proportions are listed in table 5 below.

Table 5: The number of people in the three interface test groups

Searching Interface	Number of Subjects	Percentage
GUI-Hyperlink (GH)	128	50%
Extended- Survey (ES)	64	25%
Extended- Route (ER)	63	24.7%
Total	255	

3.4 Experimental Task Design

During the experiment, the system automatically prompted the test subject with three tasks of collecting information. At the onset of the experiment, the purpose for conducting the experiment was explained to the test subjects. Afterwards, the test subjects were left alone, receiving further guidance from the system itself on the goal of each task and how to operate the interface. The system automatically detected the subjects' output, and recorded the user's operating parameters.

In this study, the main goal was to monitor the performance of the test subjects as they operated the National Taichung Library search interface. As the subjects used the interface, they were tasked to find themed material from the database. After the test subject thought that he or she had found the correct, sought-after information, he or she clicked the 'found' button, the system automatically determined if what was found was actually the target information. During the experiment, those administering the experiment used encouragement to guide the behavior of the subjects. If a subject paused for too long, they would be encouraged with kind's words, like, "It's OK! Don't Worry!" This part of the experiment took into consideration the research of Caicheng You (2011), which suggested that a child's most likely motivating factor for seeking information is 'school work', while the second most likely motivating factor is 'recreation'.

3.5 Experimental Instruments

Task 1: If the subject encountered a problem while searching for the ecological-related information, the teacher responded by telling him or her to search for reference information through the 'ecological notes database'. They then tried to locate the database using the interface.

Task 2: If the subject encountered a problem while searching for the target pictures and images, the teacher responded by telling him or her to browse the 'Tsai Comics animated series database'. They then tried to locate the database using the interface.

Task 3: If the subject encountered a problem while searching for the sports-related information, the teacher responded by telling him or her to locate the 'animated album for international sports competitions'. They then tried to find the album using the interface.

The design process was divided into four parts: the transformation of the flat-screen interface into a virtual reality space; the conversion of the flat-screen navigation design into the spatial navigation, way-finding design; the 'spatial-graphic' search interface design was divided into overview and route navigation in accordance with the development of the functional properties of the two types of interfaces; and the final part was to take the results of the second and third parts, understand them and make them more practical.

Fig. 3: National Taichung Library Children's Digital Resource Portal visual design

For the sake of experimental accuracy, the new version of the spatial icon information interface design (Figure 4) was based on the current children's Digital Resource Portal planar interface (Figure 3). Virtual Reality technology was used to build a 3D world. The color and style used are the same as those of the National Taichung Library interface.

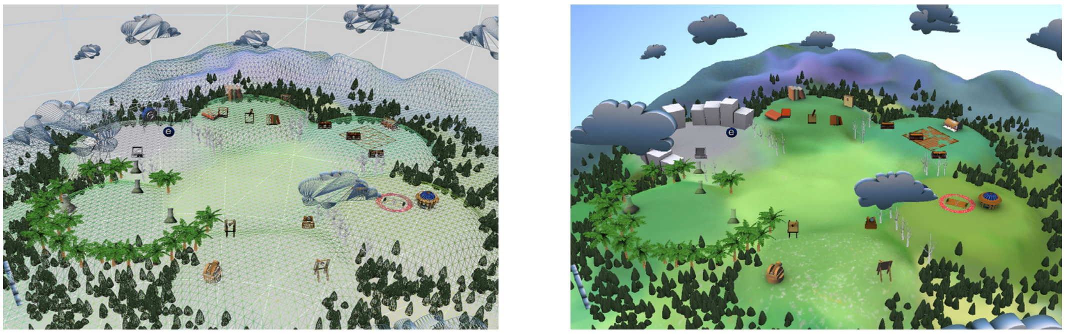


Fig. 4: Spatial icon information' interface, 3D World construction - line composition and the actual scene illustration.

4. DISCUSSION AND ANALYSIS

4.1 Comparison of the GH, ES, ER search interfaces

Table 6, Table 7, and Table 8 show how the three search interfaces (GH, ES, ER) compare in terms of efficiency. The tables list the average time spent to successfully perform a task, as well as the ANOVA, which allows for further insight into the significance of the results. The average time required by a subject to perform each task using the ES interface was less than that of the one using the ER interface. Furthermore, subjects using the GH interface had the shortest task performance time. This is in line with how its hyperlink functions offer quick link ups and shorten the time elements involved. The three tasks have significant differences ($p < .001$), therefore accept H1 assumptions.

Table 6: Task 1 - Efficiency use - comparative analysis (GH)

Interface	Numbers	Average	Standard Deviation	Standard Error	Minimum	Maximum
GH	128	80.16	115.542	10.213	6	827
ES	64	94.88	89.423	11.178	9	493
ER	63	149.63	126.613	15.952	23	567
Significant	p<.001					

Table 7: Task 2 - Efficiency use - comparative analysis (ES)

Interface	Numbers	Average	Standard Deviation	Standard Error	Minimum	Maximum
GH	128	44.05	40.367	3.568	8	264
ES	64	66.06	64.777	8.097	7	296
ER	63	123.70	110.246	13.890	16	505
Significant	p<.001					

Table 8: Task 2 - Efficiency use - comparative analysis (ER)

Interface	Numbers	Average	Standard Deviation	Standard Error	Minimum	Maximum
GH	128	14.64	21.931	1.938	5	203
ES	64	18.44	19.364	2.420	4	117
ER	63	40.19	27.942	3.520	11	172
Significant	p<.001					

4.2 Plane and Spatial Search Interfaces

The result of the experimental data analysis shows that 'plane-image' interface and the 'spatial-extendable' interface of formula" have variation in the outcomes of various performance factors (efficiency & effectiveness). In terms of efficiency, the main cause for the disparity was 'time'. This issue has been identified before by Patrick J. Lynch. Hyperlink based search interfaces create a 'page to page' search process. While way-finding based search interfaces create a 'node to node movement' process. The key advantage to a way-finding based one is that it allows for this movement experience. Whereas, when using a hyperlink based one, there is much allowance for spatial movement.

4.3 Cognitive Ability and User Efficiency

Besides developing a better understanding of how the different graphic and spatial search interfaces are used, statistical analysis of the experimental results was done to determine the different effects a child's cognitive ability has on user efficiency. As shown in Figure 5, a single-factor analysis of the 'flat-image' interface showed variance in results among the children. While, a likewise analysis of the 'spatial-extendable' interface had similar results. Yet, there were differences in the results related to the subject's cognitive ability, such as how the subject's memory capacity (MA & MV) influenced efficient use of the 'flat-image' interface, but not that of the 'spatial-extension' interface. In addition, the 'Map Memory Test (MA-3)' found differences in the efficiency of the use of three search interfaces.

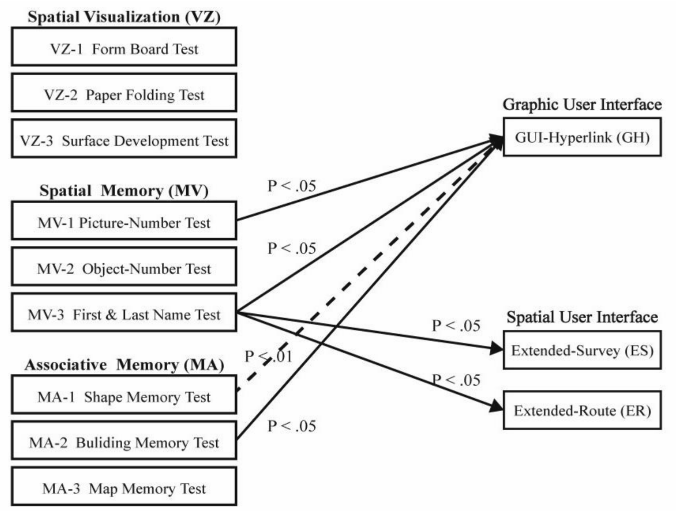


Fig. 5: Significant impact factors that affect the level of efficiency of the interface through the varying cognitive ability of children.

The design attempts to load images and text with different information in the 2D and 3D interfaces, which significantly differ because of their respective spatial capabilities. The grouping of subjects with different spatial capabilities had an impact on the use of the interfaces.

5. CONCLUSION

The first focus point of this study was to incorporate navigation and route functions into a search interface, as they are two different kinds of measuring tools. The second focus point of this study was to measure the spatial ability of the children and classify them according to those abilities. The third focus point of this study was to give children way-finding tasks using an information search interface and measure the performance results.

When comparing the three kinds of search interfaces - 'GUI-Hyperlink (GH Interface)', 'Extended-Survey (the ES interface)' and ‘Extended-Route (ER interface)' - pros and cons were found for all. The GH Interface was used the most efficiently. The ES interface was used with the most effectiveness. The Zoom View function was used the best in the ER Interface. The amount of operations performed with each interface was neutral. Comparatively speaking, the spatial- overview and route interfaces have different impacts on the different functions of spatial navigation, rotation, and scaling.

(1) The 'Associative Memory (MA)' capacity will be stimulated more by a 'flat-graphics' interface with more effectiveness and efficiency. (2) 'Mental Rotation (VZ-3)' will be caused more by an 'overview-strategic' interface. (3) The three kinds of Mental Rotation associated with 'Spatial Visual Abilities (VZ)' were not found to have any association with effective and efficient use.

To some extent, cognitive capacity can be associated with effective and efficient use, but the other operations of other performance factors, such as the number of rotations can be influenced by other factors. This study suggests that the 'spatial-rotation' ability is influenced by a different factor. In regards to 'Spatial Navigation', different rotation and scaling technology have been put together. In the present study, no correlation was identified between the scale part number and cognitive ability. There is opportunity for follow-up research to explore this aspect.

6. REFERENCES

Amichai-Hamburger Y., Kaynar, O. and Fine, A. (2007).The Effects of Need for Cognition on Internet Use. *Computers in Human Behavior, 23*, 880-891.

Arthur, P., & Passini, R. (1992). Wayfinding, People, Sign and Architecture. *Cambridge, MA: McGraw-Hill.*

Bates, M.J. (2002).The Cascade of Interactions in the Digital Library Interface. *Information Processing and Management, 38*, 381-400.

Benyon, D. (2005). Design Interactive Systems:PACT, ISBN-13: 978-0321116291.

Benyon, D. (2006). Navigating Information Space: Website Design and Lessons from the Built Environment. *PsychNology Journal, 4*(1), 7-24.

Benyon, D.R. (1998). Cognitive Ergonomics as Navigation in Information Space. *Ergonomics*, 2(41), 153-156.

Bilal, D. and Bachir, I. (2007). Children's Interaction with Cross-cultural and Multilingual Digital Libraries: I. Understanding Interface Design Representations. *Information Processing and Management, 43*, 47-64.

Carroll, J.B. (1993). Human Cognitive Abilities: A Survey of Factor Analytic Studies.; Cambridge University Press, Cambridge. ISBN-13: 978-0521387125.

Chowdhury, S., Landoni, M., and Gibb, F. (2006). Usability and Impact of Digital Libraries: A Review. *Online Information Review, 30(6)*, 656-680.

Danielson, D. (2002). Web Navigation and the Behavioural Effects of Constantly Visible Site Maps. *Interacting with Computers.*

Graham, L., Tse, T. and Keselman, A. (2006).Exploring User Navigation during Online Health Information Seeking.*AMIA 2006 Symposium Proceedingsp,* 299-303.

Holzer, M. & Kim, S. T. (2005). Digital Governance in Municipalities Worldwide (2005), from: http://unpan1.un.org/intradoc/groups/public/documents/ASPA/UNPAN022839.pdf .

Hutchinson, H., Rose, A., Bederson, B.B., Weeks,A.C. and Druin, A. (2005).International Children's Digital Library: A Case Study in Designing for a Multilingual, Multicultural, Multigenerational Audience, Information Technology and Libraries, (March), 4-12.

Hutchinson, H.B.,Druin, A. and Bederson, B.B. (2007). Supporting Elementary-Age Children's Searching and Browsing: Design and Evaluation Using the International Children's Digital Library. *Journal of the American Society for Information Scienceand Technology,* 58(11), 1618-1630.

International Children's Digital Library (2002). Retrieved (Dec) 19, from: http://en.childrenslibrary.org/about/mission.shtml

Jankowski, J. (2011). A Taskonomy of 3D Web Use.Proceedings of the 16th International Conference on 3D Web Technology.Paris, France, p.93-100. Retrieved Dec. 19, from:http://delivery.acm.org/10.1145/2020000/2010443/p93-jankowski.pdf?ip=140.124.81.78&acc=ACTIVE%20SERVICE&CFID=58676626&CFTOKEN=26299245&__acm__=1324294029_001043804ce78a3a397db2a171415d38

Kalbach, J. (2007).*Designing Web Navigation: Optimizing the User Experience.O'Reilly*, ISBN-13: 978-0596528102.

Kasper & Morten. (2011).The Notion of Overview in Information Visualization. *Human-Computer Studies*, 69, 509–525.

Kato, Y. & Takeuchi, Y. (2003), Individual Differences in Way-finding Strategies. *Journal of Environmental Psychology, 23*, 171-188.

Krug, S. (2005). Don't Make Me Think: A Common Sense Approach to Web Usability, (Ed. 2nd), ISBN-13: 978-0321344755.

Kyllonen, P. C., Lohman, D. F., & Woltz, D. J. (1984). Componential Modeling of Alternative Strategies for Performing Spatial Tasks. *Journal of Educational Psychology*, 76, 1325-1345.

Lawton, C. A. (1996). Strategies for Indoor Way-finding: the Role of Orientation. *Journal of Environmental Psychology*, 16, 137-145.

Lu, Y.L. (2010). Children's Information Seeking in Coping with Daily-Life Problems: An investigation of fifth- and sixth-grade students, *Library & Information Science Research, 32*, 77-88.

Lynch, P.J. and Horton, S. (2009). Web Style Guide, 3rd edition: Basic Design Principles for Creating Web Sites, (Ed. 3rd), ISBN-13: 978-0300137378.

Macaulay, C., Benyon D.R. and Crerar, A. (2000). Ethnography in Design: Uncovering New Artifacts. *International Journal of Human Computer Studies*.

Munro, A., Höök K. and Benyon, D.R. (1999).Social Navigation of Information Space, A. Munro, K. Höök, D.R. Benyon, Editors Springer, London.

Nielsen, J. (2000).Jakob Nielsen's Alertbox: Is Navigation Useful Retrieved Dec. 19,2011 from:http://www.useit.com/alertbox/20000109.html

Richard Anderso. (2002). Coming Together to Explore the Intersections of HCI, Experience Design, and Information Architecture. *Magazine interactions - Interface design,* 9(2), 109-111.

S.J. Westermana, J. Collinsb, T. Cribbin. (2005). Browsing a Document Collection Represented in Two- and Three-dimensional Virtual Information Space. *Human-Computer Studies,* 62, 713-736.

Spence, R. (1999). A Framework for Navigation. *International Journal of Human–Computer.*

ASSESSING THE PEDAGOGICAL VALUE OF AUGMENTED REALITY-BASED LEARNING IN CONSTRUCTION ENGINEERING

Arezoo Shirazi & Amir Behzadan
University of Central Florida, U.S.A

ABSTRACT: *This paper presents the latest findings of authors' work in design and assessment of an augmented reality pedagogical tool for construction engineering education. Previous work has extensively discussed the need for suitable learning tools and information delivery methods to enhance the quality of engineering education. However, developing a methodology with measurable outcomes that can assist in transforming conventional instructional techniques is not a trivial task and requires a meticulous approach. Within the educational research community, it is commonly accepted that instrumental aids, if properly used, can be effective controllers of human learning. This prospect coupled with the fact that technological advancements and mobile tools have become ubiquitous parts of our lives, motivated the authors to explore the possibility of using smartphones and tablet devices as instrumental aids to improve the quality of classroom teaching and learning. In particular, a context-aware augmented reality application was used to create a pop-up book by superimposing 3D graphics (virtual models, animations) and multimedia (images, videos, sounds) over the pages of a construction engineering textbook. This enabled students to watch, interact with, and learn abstract topics in construction equipment and methods in multiple contexts. The hypothesis of this research is that by establishing a contextual connection between ordinary textbook materials and technologies that students use in their daily routines, student engagement in the learning process improves, students can focus their attention to critical concepts, and instructors will be able to better evaluate students' progress toward conceptual understanding. In this regard, effectively measuring knowledge transfer and metacognition plays a vital role. To achieve this, several assessment techniques such as teacher-designed feedback forms, group-work evaluations, pre- and post- surveys, and exam evaluations are used to assess all three aspects of the learning process (replicative, applicative, and interpretive). Results, technical discussions, and recommendations are provided in this paper.*

KEYWORDS: *augmented reality, construction education, pedagogical, cognitive, collaboration, classroom assessment techniques, context-aware.*

1. INTRODUCTION

To many students who are pursuing degrees in science, technology, engineering, and math (STEM), instructional techniques that heavily rely on traditional methods (e.g. note taking, handouts, memorization) to convey basic knowledge and skills about fundamental theories and applications are considered obsolete and not engaging. The new generation of students is technology savvy with high knowledge of and interest in social media, mobile technologies, and strategy games (Friedrich et al. 2009). Several school systems have recently initiated plans to deploy various types of classroom technology aimed at providing students with higher quality education with long-lasting impact. However, studies indicate that using technology without a suitable pedagogical structure may not yield desired outcome and can even have negative impact on student learning and long-term knowledge retention (Cristia et al. 2012). Therefore, having a technology-based pedagogical learning tool besides traditional learning methods could potentially enhance the learning quality (Echeverría et al. 2012; Roschelle et al. 2010).

Among several classes of digital technology, Pan et al. (2006) discussed that using virtual learning applications may result in an efficient and effective learning. More recently, a growing number of schools and educational institutions have shown interest in adopting such technologies in order to create productive educational environments. It is very likely that within the next several years, instructional techniques that benefit from new emerging technologies such as virtual reality (VR) and augmented reality (AR) will become standard components of STEM education. Such techniques will better assist teachers to be more effective when explaining abstract topics, while providing students with a means to collaborate on a common problem which ultimately strengthens their teamwork, communication, and critical thinking skills. This paper presents the latest results of an ongoing research project which aims at exploring the potential of mobile context-aware AR in STEM education. For

Citation: Shirazi, A. & Behzadan, A. H. (2013). Assessing the pedagogical value of augmented reality-based learning in construction engineering. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

proof-of-concept experiments and to validate the usability of the developed methodology, different scenarios from the construction and civil engineering domains are used. However, as outlined later in this paper, the final product of this research is sought to be generalizable and thus, the application domain will be ultimately expanded to other STEM disciplines.

2. AUGMENTED REALITY: A BRIEF INTRODUCTION

AR generates three-dimensional (3D) virtual contents on top of the views of the real world and creates an interactive interface which includes both real world and virtual objects (Azuma 1997). In essence, AR can be simply defined as a visualization paradigm that combines digital information with the real world (Pence 2010).

Although the more widely known VR visualization technology has been used during the past several years in STEM education, researchers predict that very soon, AR will supersede VR in terms of widespread use and educational impact (Pence 2007). Studies also suggest that many people are still uncomfortable with navigating around and interacting with a fully virtual world (Pence 2010). To this end, one of the advantages of AR is that it does not completely eliminate the real world from a user's experience, and hence, users have a more realistic sense of presence in the visualization experiment. In addition, AR provides a convenient interface for constructivism and discovery-based learning, spatial understanding, and social interaction, while it allows users to learn through making mistakes without having to worry about real world consequences (Behzadan and Kamat 2012). In terms of key technological components, AR incorporates several important aspects of visualization research including but not limited to the proper alignment of real and virtual worlds (a.k.a. registration), and real time interaction and feedback (Behzadan and Kamat 2005; Martin-Gutierrez et al. 2012). While researchers are still working on the psychological aspects resulting from the integration of AR in education, several studies have so far validated the technological effectiveness of AR in the learning process (Lindgren 2012; Martin-Gutierrez et al. 2012).

3. RESEARCH MOTIVATION

This research is motivated by two important observations regarding the new generation of students: (1) technology is embedded in their daily tasks outside the classroom, and (2) they have easy access to mobile devices. It is almost impossible to separate students from their technology-enabled devices or ask them to think and act differently than how they do outside the classroom. Rather, a more reasonable approach is to find ways to create a seamless transition between the outside world and the classroom environment. Surprisingly, a large percentage of students already have a good knowledge of terms such as VR and AR, but cannot or do not know how to relate these tools to their learning experience.

The authors recently administered a student survey in an undergraduate (junior-level) construction and civil engineering class of 88 students. As shown in Figure 1, 89% of responders indicated that they owned a smartphone, a tablet device, or both. Out of this population, 88% were familiar with VR, and 37% were familiar with AR. A solid majority of respondents (94%) agreed that they would learn better if instructors used interactive visualization and animation in the classroom (see Figure 2). The same survey revealed that a large percentage of students were visual and/or kinesthetic learners. In addition, 51% of students suggested that they would learn better if they worked in a collaborative setting (e.g. working in a team) where they played a role in the learning process. The results of this survey implied that many students tend to learn better and faster in an environment where they can see physical models or visual representations of the abstract concepts they are taught, or carry out individual or team activities as opposed to just listening to a lecture.

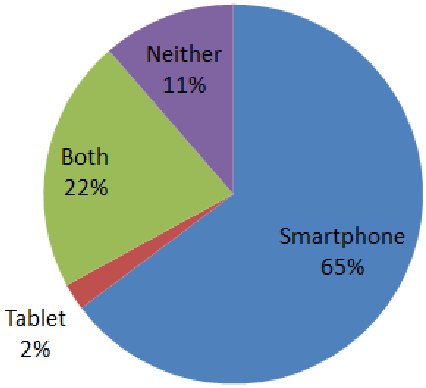


Fig. 1: The survey revealed that a large percentage of students own a smartphone, a tablet device, or both.

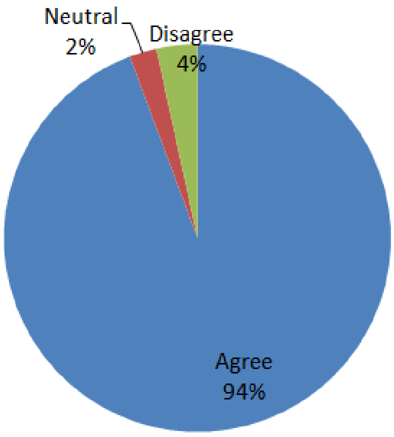


Fig. 2: A solid majority of students agreed to the statement: "I am a visual learner. I learn better when the instructor uses 2D/3D visualization or multimedia to teach abstract engineering and scientific topics".

In another study conducted by Felder and Silverman (1988), it was shown that most engineering students are visual and active learners. More recently, Dong et al. (2013) highlighted the same facts in their survey of undergraduate civil engineering students. These and similar studies justify the need for and present the unique opportunity to transform conventional pedagogical methods by taking advantage of recent technology advancements in an effort to help STEM students better relate the abstract knowledge they learn in the classroom to challenging problems they may face in the outside world. Interactive AR visualization applications can be effectively designed and launched on many existing small portable devices (e.g. smartphones, tablets, PDAs) to support this goal.

From a pedagogical perspective, an AR-based learning tool can draw students' attention by providing an easy-to-use and navigate interface, and creating a multi-user collaborative environment that enables natural interactions to enhance communication and better convey spatial cues (Chen 2006; Shelton and Hedley 2004). Other advantages of handheld AR which distinguish it from other visualization technologies are the portability of smartphones and tablets and that they are all equipped with built-in cameras (Kesim and Ozarslan 2012) that can be readily used to capture real world views.

4. LEARNING THEORY-BASED JUSTIFICATION

John Dewey (1859-1952) was an American psychologist and educational reformer who established the philosophy of pragmatism in education. Pragmatism is a philosophical term that describes the proper connection between practice and theory. It states that theory and practice continuously convert to one another, a cycle which is also referred to as intelligent practice. Existing methods of information delivery to students lack the intelligent practice aspect as they predominantly use (at best) a combination of computer slides and board work and do not fully support student participation in the discussions. Instructors who use these methods in classroom most often end up giving lectures while students are busy taking notes and trying to relate instructor's words to the contents of the slides. With this in mind, the authors applied the concept of intelligent practice to their work by providing students with context-aware AR pop-up books and asking them to collaboratively learn and practice the course material. This approach was reinforced by the prospect that through the presence of a social classroom environment and by allowing constructive discussion and collaboration between educators, a better alternative to the traditional teaching and learning experience can be created and deployed. Mayer and Moreno (1998) discussed that simply adding pictures to words does not guarantee an improvement in learning. Therefore, in this research, AR visualization was used to superimpose several other modes of multimedia information (including 2D and 3D models, videos, sounds) to potentially foster student learning.

Evidently, one of the pitfalls of relying too much on technology is that it does not necessarily guarantee effective learning and in fact, inappropriate use of technology can be distracting and even hinder learning (Bransford 2000). In light of this, in the presented work, digital technology such as smartphones and tablet devices is used not to replace the instructor but rather to supplement traditional instructional methods with new interactive technology. Another advantage of using this newly designed learning strategy is to shift the analytic focus from individual learners to group learners who participate in the social world and turn the cognitive process into a more encompassing view of social practice. Together, interactive learning and social interaction constitute what is commonly known as constructivism (Bruning et al. 1999).

It was anticipated that enhancing the contents of an ordinary textbook with computer-generated 2D and 3D models, still images, and other types of multimedia (e.g. movies, sounds) and using technologies such as smartphones and tablet devices to deliver such virtual information to the students would results in a more engaging learning experiment where students could ask more questions and gain more information. In addition, students who may have been overwhelmed by the sheer volume of information and course materials from other classes during the day would perceive this technology-enabled teaching environment as a different "out-of-the-box" setting which is more interesting to experience. Putting all these together, it was hypothesized that the new AR-based learning tool and the designed pedagogical methodology can bring every aspect of a successful learning process together, namely context, people, objects, and technology (Dewey 1959). As a result, educators will be better able to relate abstract theories to the real world problems, and take advantage of others' experience, thinking and reflection, interaction, and share in common life. Therefore, the lack of (1) organic connection, (2) motivation, and (3) connection between curriculum and real world, the three "evils" as suggested by Dewey (2010) will be eliminated.

Moreover, this research tried to investigate if using the new pedagogical tool could fulfill the three aspects of knowing, namely replicative, applicative, and interpretive through students responding to new information, participating in group work, and explaining the concepts to each other. To achieve this and considering Schwartz's theory about combining replicative, applicative, and interpretive aspects to achieve the best outcomes from the learning procedure (Schwartz et al. 2005), measures related to these three aspects were built in the designed assessment procedure and the effectiveness of the developed methodology in terms of short-term adaptability and long-term retention efficiency was evaluated.

5. METHODOLOGY

The main focus of the research presented in this paper is to design, implement, and assess an AR visualization platform that can be launched on mobile devices running on Android or iOS operating systems, and provide students with a means to see and interact with the contents of their textbooks. Since a mobile device provides the user with both input (through its built-in camera) and output (through its display) capabilities, the user does not have to wear extra peripheral devices such as AR goggles or head-mounted displays (HMDs) and thus, is less likely to be distracted during the learning experiment. The tangible product of this research is an AR pop-up book which in essence, is very similar to a traditional textbook but is enhanced with multimedia and context-aware 3D graphics capabilities. Students are able to use their books without the need to carry any additional devices or hardware. However, as shown in Figure 3, when looked at through a mobile device (e.g. smartphone, tablet), 3D graphics (models, animations) and multimedia (e.g. video, sound) corresponding to the content of each page is displayed to the student.

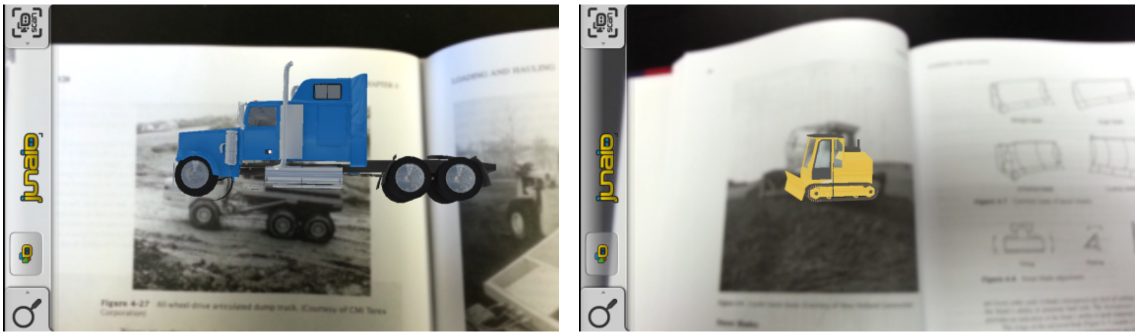


Fig. 3: Computer-generated virtual content is delivered to students via their mobile devices as they hover over different images of the textbook.

Using an AR pop-up book can be the first step to immerse students in their course topics. Billinghurst et a. (2001) showed that using an AR pop-up book results in collaboration in classrooms since it can bring together three levels of interaction: using a physical object, using an AR object, and immersing in a virtual space. In the following paragraphs, basic components of the developed platform are described in more detail:

Scanning and Markers: A key component of any AR application is accurate registration of virtual contents inside the real world space. Registration guarantees that real and virtual objects are always aligned inside the user's viewing frustum (Kamat and Behzadan 2006). There are two registration techniques that are commonly employed in AR: marker-less, and marker-based. In this research, the marker-based type is used. In particular, students first use their handheld devices to scan a 2D pattern (see Figure 4), which is known as a Quick Response (QR) code. The QR code helps identify the proper mapping between virtual information and the real world. Once the QR code is scanned and identified, subsequent scanning of predefined AR markers (a.k.a. tracking images) printed on the inside pages of the AR pop-up book will result in specific virtual contents superimposed on top of the markers. When the tracking image is visible through the device's camera, the corresponding virtual information is displayed to the student.

AR Publishing Software: In this research, an open-source third-party application for Android and iOS devices named Junaio was used as an entry point for developing and publishing context-aware AR experiments (Junaio 2012). Using this application, computer-generated information about different locations or objects can be linked via their corresponding channels. A channel is in fact a link to a remote server where the content is stored. Junaio employs two different channel types: location-based channels, and GLUE channels. When location-based channels are used, users can view the real world through the built-in camera of their mobile devices while the application overlays virtual information about points of interest (POIs) in the user's surrounding as soon as they fall within the user's viewing frustum. Users can hold their handheld devices up and look around to see virtual objects floating over different POIs. Using GLUE channels, on the other hand, one can attach or "glue" virtual 3D models, images or movies to any real world object. These 3D models can be linked to sound or video files as well as websites or images.

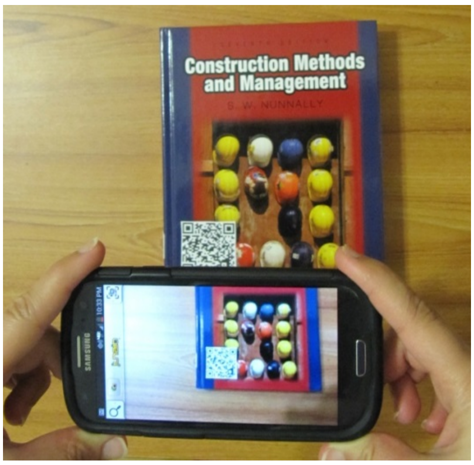
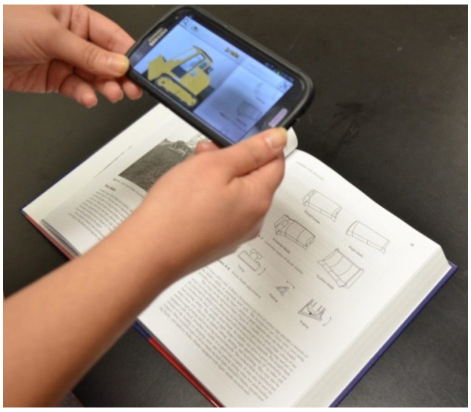


Fig. 4: Each student first scans a QR code using the built-in camera of his or her mobile device.

In this research, Junaio GLUE channels were used to create the AR interface of the AR pop-up book for construction and civil engineering students. The authors "enhanced" a sample chapter from a construction methods and management textbook (Nunnally 2007) by augmenting different types of virtual information (e.g. 3D models, videos, sound clips, and 2D images) on existing figures, tables, and diagrams (used as AR tracking images). Figure 5 shows snapshots of single-user and multiple-user feasibility experiments conducted using the developed mobile application.

A very important and convenient feature of the developed application is that all computer-generated virtual information are stored and updated on a host server maintained by the application developers. End users (i.e. students) do not need to download large volumes of information onto their mobile devices. Instead, they simply download and install a small application that will, in turn, communicate with the online data server and pull necessary information in real time. Given that students and instructors have easy access to Wi-Fi internet on campus and that 3G-4G mobile internet is becoming more widespread, this approach significantly reduces the processing time while giving application developers the flexibility to update or modify parts of the application from a remote server without having to physically access and run updates on each and every mobile device used by the students. The AR application is programmed using the Hypertext Preprocessor (PHP). PHP is a widely-used open source general-purpose scripting language that is especially suited for web development and can be embedded into the HyperText Markup Language (HTML).



(a) A single user views virtual contents overlaid on a book page.

(b) Two users simultaneously view virtual contents overlaid on two different pages.

Fig. 5: Computer-generated virtual content is superimposed and displayed over printed images of the textbook.

6. CLASSROOM ASSESSMENT PROCEDURE

After carefully designing the structure of the pedagogical framework and implementation strategies, the developed methodology was tested in a real classroom and student performance data was collected to evaluate if any potential improvement was achieved. In particular, a two-stage implementation process is planned for this research. In the first stage, the developed pedagogical technique is tested through several classroom experiments conducted in the authors' institution. The second stage (which is part of the future work) will include a collaborative effort among several educational institutions to assess the benefits of the developed learning tool in multiple courses using larger and more diverse student populations.

During the first stage of the assessment process, the authors implemented the mobile AR platform in an undergraduate course titled "CCE4004 – Construction Methods" offered every spring semester by the Department of Civil, Environmental, and Construction Engineering at the University of Central Florida (UCF). Two "mystery lectures" and three different assessments were performed. The course was offered in spring semester 2013 and had a total enrollment of 16 students. Table 1 shows the calendar of the assessment procedure. For the purpose of this experiment, "construction site investigation" was selected as the lecture topic. This topic was not previously covered in the course and thus, students were mostly unfamiliar with it. Also, students were not aware of the topic of mystery lectures nor did they know about the content of the other group's lecture prior to attending their own lecture. However, all 16 students were given a questionnaire about a week prior to the mystery lectures and basic personal information (e.g. gender, program of study), as well as information about their level of familiarity with some technical terms (e.g. VR, AR), and possession of computing devices (e.g. laptops, tablets, smartphones) were collected. Each student was assigned a random ID number and the collected information was used to better assign students to either group. Group A (control group) attended the first mystery lecture where material was delivered using conventional instructional methods such as PowerPoint slides, lecture notes, and ordinary textbook. Group B (test group), attended the second mystery lecture were the same topic was delivered using the developed AR-based information delivery platform and pop-up books. Group B was divided into teams of two people (a total of four teams) and each team was allowed to work collaboratively and interact with the designed features of the mobile platform on their own tablets or smartphones, as shown in Figure 6.

Table 1: Calendar of the assessment procedure

Assessment Component	**Date**
Pre-survey Questionnaire (16 students): Background information about program of study, gender, familiarity with terms such as VR and AR, and possession of mobile devices	Tuesday, March 26, 2013
Group A Mystery Lecture (8 students): Pre-lecture test at the beginning of the lecture, delivery of conventional lecture, post-lecture test at the end of the class	Tuesday, April 2, 2013
Group B Mystery Lecture (8 students): Pre-lecture test at the beginning of the lecture, delivery of lecture using the new AR and pedagogical tools, post-lecture test at the end of the class	Thursday, April 4, 2013
End of Semester Test (16 students): Give the same test simultaneously to all students without their prior knowledge about one month after the mystery lectures (at the final exam)	Tuesday, April 30, 2013

Group A – conventional lecture

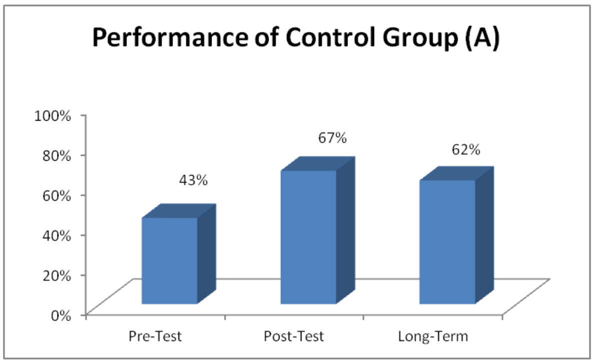
Group B – AR information delivery platform

Fig. 6: Two mystery lectures were conducted during the first stage of the assessment process.

In order to effectively assess the benefits of the new tool and analyze its impacts on the learning process, and considering different aspects and limitations of available assessment techniques, the authors selected nine different classroom assessment techniques (CATs) from a list of fifty standard CATs as introduced by Cross and Angelo (1988). Background knowledge probe, memory matrix, categorizing grid, and approximate analogies were among the techniques that were used. These CATs helped design an 18-question test that was used both prior and after each mystery lecture to systematically evaluate if the new AR-based learning tool had real and practical advantages when used in actual classroom settings. Also, as shown in Table 1, in addition to the pre- and post-lecture tests, an end-of-semester test including the same 18 questions was simultaneously given to all 16 students (without their prior knowledge) to assess if the knowledge they gained during the mystery lectures was retained with them in the longer term. Results and analysis are discussed in the next Section.

7. RESULTS

Figure 7 shows a summary of the analyzed data collected from students in Groups A and B. As shown in this Figure, students in Group A on average gave correct answers to 43% of the test questions prior to the lecture. After the lecture, the same test was given and this time, students on average gave correct answers to 67% of the questions. On the other hand, students in Group B on average gave correct answers to 29% of the test questions prior to the lecture. After the lecture, the same students on average gave correct answers to 69% of the questions. Through analyzing individual students' data, it was revealed that the performance of students in Group A on average improved by only 24%, while the same measure for Group B was about 40% (See Figure 8). In addition, as shown in Figure 7, when the same set of questions was given to all students one month later in order to evaluate long-term information retention, students in Group A gave correct answers to 62% of the questions while students in Group B answered 65% of the questions correctly. These results implied that compared to their post-lecture tests, Group A students retained 93% and Group B students retained 94% of the information in a period of one month.



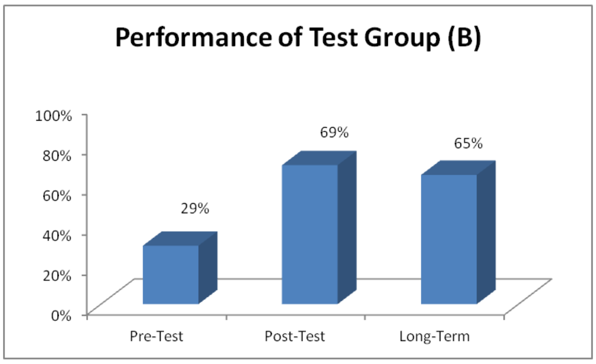


Fig. 7: Comparison of the pre- and post-test results as well as long-term retention of information for Group A (control group) and Group B (test group).

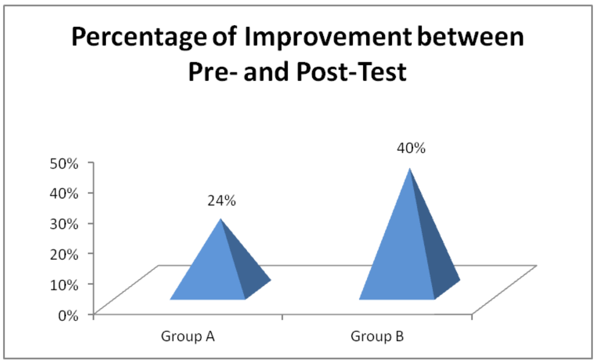
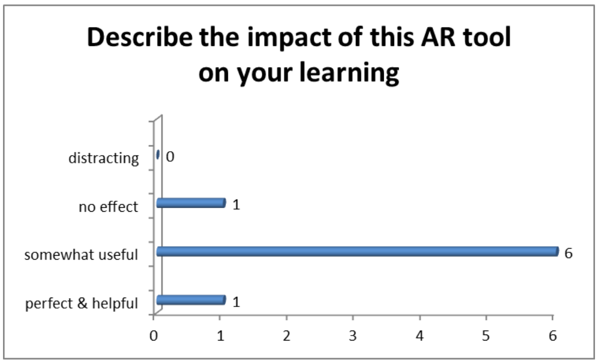


Fig. 8: Assessment results showed a higher performance improvement in Group B students who used the AR-based mobile platform to learn the course material.

In addition to performance data, students in Group B answered a series of questions about their perception of the AR-based learning tool upon the completion of the mystery lecture. These questions were designed using evaluation assessment techniques such as teacher-designed feedback forms and group-work evaluation. As shown in Figure 9, according to this survey, 7 out of 8 (i.e. 87.5%) students stated that the AR tool was "somewhat useful" or "perfect and helpful" in their learning. None of the students described the tool as being "distracting".



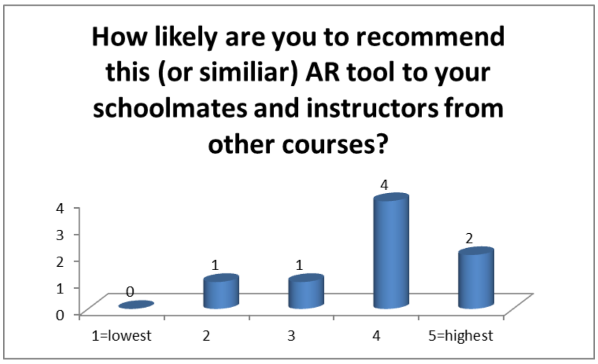


Fig. 9: Results of perception survey showed a significant interest in part of the students to use the developed AR-based learning tool in the classroom.

Using a 5-point Likert scale, collected data indicated that 77.5% of students (calculated by taking a weighted average of all responses) would recommend the use of this tool to their schoolmates and instructors in other courses.

8. CONCLUSIONS AND FUTURE WORK

It was observed that while today's students may have a very good knowledge and understanding about visualization technologies such as VR and AR, they are still not fully taking advantage of these tools in their learning process. In this paper, latest findings of an ongoing research project which aimed at using mobile context-aware AR in construction and civil engineering instruction were presented. In particular, the authors developed a pedagogical methodology for improving the quality of learning through transforming traditional instructional delivery techniques into technology-based learning. Students used their smartphones or tablet devices to download a small mobile application which enabled them to augment the contents of their textbooks by computer-generated information (e.g. 2D images, 3D models, movies, and sound). An academic assessment process to validate the effectiveness of the developed instructional material delivery technique was the next step. To this end, the authors conducted a pilot assessment study by dividing a class of 16 students into two groups. The control group (Group A) attended an ordinary lecture, while the test group (Group B) was asked to interact with the lecture material using their mobile devices and AR pop-up books. Data describing student performance was collected from both groups using several classroom assessment techniques adopted from Cross and Angelo (1988). The findings indicated that the performance of students in Group A was only improved by about 24% after attending the regular lecture while the performance of students in Group B was improved by more than 40% after attending the AR-enabled lecture. Further analysis also revealed that compared to their post-lecture tests, Group A students retained 93% and Group B students retained 94% of the information in a period of one month. Overall, data obtained from the developed assessment procedure showed that interactive mobile AR visualization tools coupled with a collaborative learning experience positively affected student learning. The authors are currently working on the design and implementation of several other experiments using larger and more diverse student populations. Ultimately, the findings of this research will be generalized and the application domain will be expanded to other STEM disciplines.

9. REFERENCES

Azuma R. T. (1997). A survey of augmented reality, *Presence-teleoperators and virtual environments*, Vol. 6, No. 4, 355-385.

Behzadan A. H. and Kamat V. R. (2005). Visualization of construction graphics in outdoor augmented reality, *Proceedings of the 37th conference on winter simulation*, IEEE, 1914-1920.

Behzadan A. H. and Kamat V. R. (2012). A framework for utilizing context-aware augmented reality visualization in engineering education, *Proceedings of the 2012 conference on construction applications of virtual reality (CONVR)*, National Taiwan University, 292-299.

Billinghurst M., Kato H. and Poupyrev I. (2001). The magicbook-moving seamlessly between reality and virtuality, *Computer graphics and applications*, IEEE, Vol. 21, No. 3, 6-8.

Bransford J. (2000). How people learn: Brain, mind, experience, and school, *National academies press*.

Bruning R. H., Schraw G. J. and Ronning R. R. (1999). Cognitive psychology and instruction, Prentice-Hall, Inc., One Lake Street, Upper Saddle River, NJ 07458.

Chen Y. C. (2006). A study of comparing the use of augmented reality and physical models in chemistry education, *Proceedings of the 2006 international conference on virtual reality continuum and its applications*, ACM, 369-372.

Cristia J., Ibarrarán P., Cueto S., Santiago A. and Severín E. (2012). Technology and child development: Evidence from the one laptop per child program, *IZA discussion paper*, 6401.

Cross K. P. and Angelo T. A. (1988). Classroom assessment techniques. A handbook for faculty, office of educational research and improvement (ED), Washington, DC.

Dewey J. (2010). The school and society and the child and the curriculum. *Digireads.* Com.

Dewey J. (1959). The child and the curriculum, University of Chicago press.

Dong S., Behzadan A. H., Chen, F. and Kamat V. R. (2013). Collaborative visualization of engineering processes using tabletop augmented reality, *Advances in engineering software*, Vol. 55, 45-55.

Echeverría A., Améstica M., Gil F., Nussbaum M., Barrios E., and Leclerc S. (2012). Exploring different technological platforms for supporting co-located collaborative games in the classroom, *Computers in human behavior*, Vol. 28, No. 4, 1170-1177.

Felder R. M., and Silverman L. K. (1988). Learning and teaching styles in engineering education, *Engineering education*, Vol. 78 No. 7, 674-681.

Friedrich K., Sellers S. L., & Burstyn J. (2009). Thawing the chilly climate: Inclusive teaching resources for science, technology, engineering and math. Chap 9, 133-144.

Junaio (2012). Junaio: your mobile companion, *Junaio Blog, <http://www.junaio.com/>*. (Dec. 15, 2012).

Kamat V., and Behzadan A. (2006). GPS and 3DOF tracking for georeferenced registration of construction graphics in outdoor augmented reality, *Lecture notes in computer science (Intelligent computing in engineering and architecture)*, Vol. 4200, 368-375.

Kesim M., and Ozarslan Y. (2012). Augmented reality in education: Current technologies and the potential for education, *Procedia-social and behavioral sciences*, Vol. 47, 297-302.

Lindgren R. (2012). Generating a learning stance through perspective-taking in a virtual environment, *Computers in human behavior*, Vol. 28, No. 4, 1130–1139.

Martin-Gutierrez J., Guinters E. and Perez-Lopez D. (2012). Improving strategy of self-learning in engineering: laboratories with augmented reality, *Procedia-social and behavioral sciences*, Vol. 51, 832-839.

Mayer R. E. and Moreno R. (1998). A cognitive theory of multimedia learning: Implications for design principles, *Proceedings of the annual meeting of the ACM SIGCHI conference on human factors in computing systems,* Los Angeles, CA.

Nunnally S. W. (2007). Construction methods and management, Prentice Hall, Upper Saddle River, New Jersey.

Pan Z., Cheok A. D., Yang H., Zhu J. and Shi J. (2006). Virtual reality and mixed reality for virtual learning environments, *Computers & graphics*, Vol. 30, No. 1, 20-28.

Pence H. E. (2007). The homeless professor in Second Life. *Journal of educational technology systems*, Vol. 36, No. 2, 171-177.

Pence H. E. (2010). Smartphones, smart objects, and augmented reality, *The reference librarian*, Vol. 52, No. 1-2, 136-145.

Roschelle J., Rafanan K., Bhanot R., Estrella G., Penuel B., Nussbaum M. and Claro S. (2010). Scaffolding group explanation and feedback with handheld technology: Impact on students' mathematics learning, *Educational technology research and development*, Vol. 58, No. 4, 399-419.

Shelton B. E. and Hedley N. R. (2004). Exploring a cognitive basis for learning spatial relationships with augmented reality, *Technology, instruction, cognition and learning*, Vol. 1, No. 4, 323.

Schwartz D. L., Bransford J. D. and Sears D. (2005). Efficiency and innovation in transfer, *Transfer of learning from a modern multidisciplinary perspective*, Vol. 1, No. 51.

IMPROVING THE KNOWLEDGE AND MANAGEMENT OF THE HISTORICAL BUILT ENVIRONMENT WITH BIM AND ONTOLOGIES: THE CASE STUDY OF THE BOOK TOWER

Danilo Di Mascio
Department of Architecture, G. d'Annunzio University, Pescara-Chieti, Italy

Pieter Pauwels
Institute for Logic, Language and Computation, University of Amsterdam, The Netherlands

Ronald De Meyer
Department of Architecture and Urban Planning, Ghent University, Ghent, Belgium

ABSTRACT: *The historical built environment is acknowledged as a valuable material and cultural resource that needs to be preserved. Usually, however, there are difficulties that do not allow to effectively analyze and document it. Difficulties arising from building characteristics (e.g. irregular shape), site characteristics (e.g. particular natural or artificial context) or other exceptional events (e.g. natural disasters) make it impossible to use only traditional theories, tools and techniques. On the contrary, digital technologies give the opportunity to improve and expand the comprehension of complex artifacts. The objective of our research is to elaborate and propose a theoretical and methodological framework to improve the comprehension and management of the historical built environment with digital technologies. The recorded information can be essential to plan and manage a recovery plan and/or a maintenance program taking into consideration also aspects linked to cultural diversity and environmental sustainability. In this paper we will deal mainly with the constructive and relational characteristics of historical buildings. The constructive characteristics point out the constructive system of an artifact (number, type and material of technical elements, etc.), whilst the relational characteristics represent the relations among the internal components of the artifact and other external elements that could be of various kind (persons, places, etc.). To analyze and document these characteristics we used mainly Building Information Management (BIM) software (Revit) and an ontology editor (TopBraid Composer). Revit was used for the digital 3D reconstruction and TopBraid Composer was used to represent and organize the relational characteristics. Both were applied to a case study: the Book Tower in Ghent, Belgium. This is one of the most important historical (20th century) buildings in the city of Ghent. Through the paper we will show the methodology we used, the issues we tackled and possible future developments.*

KEYWORDS: *3D, BIM, digital reconstruction, historical built environment, information, knowledge organization, ontologies*

1. INTRODUCTION

The built environment represents a precious material and cultural resource that has to be preserved for the future generations. It is not possible to think of a development without conservation, especially in a time like the present one, where interventions on buildings are more frequent than the ones related to the realization of new buildings. The built environment is the result of an evolutionary growing and conservation process which lasts centuries; and its buildings are valuable deposits of meaning and knowledge. This meaning and knowledge includes information regarding constructive techniques, energy and materials. A proper preservation of the built environment is expressed by a sustainable use of materials and territories, but also by an awareness of the importance of the cultural roots of the elements in this built environment, which are precious expressions of identity and diversity that have to be preserved for future generations (Di Mascio, 2012). In the present paper we will draw particular attention on the historical built environment. The artifacts belonging to this heritage have specific architectural, artistic and cultural features that are valuable to be maintained for future generations. To understand and assess the qualities of the historical built environment it is important both to visit personally the buildings in order to have a direct experience of their most relevant characteristics and to collect and analyze all the available information from

Citation: Di Mascio, D., Pauwels, P. & De Meyer, R. (2013). Improving the knowledge and management of the historical built environment with BIM and ontologies: the case study of the book tower. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

different sources. The analysis to be undertaken during these actions can be very diverse depending on the specific characteristics of the building that has to be studied. The value of the historical built environment always deals with cultural aspects linked to history (including economic and social aspects), architecture and arts, thus going beyond the material and functional value of the building.

2. THE CONSTRUCTIVE AND RELATIONAL CHARACTERISTICS

Each single building is characterized by a high number of material and immaterial characteristics. The latter represent all the intangible aspects such as size, lights, shadows, colors, paths, spaces, relationships, etc. (Di Mascio, 2012). They are not only the result of a culture linked to the physical features of a place, but also to aspects linked to the cultural and historical context, including artistic movements, technical-scientific discoveries, commercial exchanges, etc. In this paper we will deal with two characteristics that we retain useful to improve the comprehension and the management of any building/artifact pertaining to the historical built environment: the constructive and relational characteristics. These two types of characteristics are defined as follows:

- Constructive characteristics: The concept of constructive characteristics indicates the constructive system of an artifact, referring to the materiality, number and type of technical elements that compose it, to which requirements it corresponds and to how they are connected/assembled. For example, for a standard brick wall with a simple door opening, these constructive features capture the dimensions of wall and door, along with their material characteristics, the way in which they are assembled or combined, and so forth.
- Relational characteristics: The concept of relational characteristics indicates the relational system both between the components within the artifact, and between these and other external elements that could be of various nature (persons, places, documents, etc.). The explanation of these relations allows to deepen and enrich the knowledge of the artifact, as if it unveils itself as a system of relations belonging to a bigger system. For the same example of the standard wall with door opening, these relational features capture not only the relation between wall and door, but also the relation between wall and surrounding spaces, between door and architect, and so forth.

Knowledge of the constructive characteristics is essential when appropriate maintenance actions or similar interventions are required for the preservation of the quality of the artifact; but all these features are also fundamental to carry out other analyses that involve evolutionary, energy, structural, perceptive characteristics. Knowledge of the relational features allow the comprehension and description of the artifact with more details and the improvement of its management. In the following section, we document the way in which we aim to capture this information and represent it in a reusable format using the appropriate technologies.

3. DISCOVERING THE INVISIBLE: METHODOLOGICAL APPROACH

The historical built environment is constituted by a variable number of artifacts and buildings that, in most cases, are not well documented. The lack of an appropriate documentation to manage maintenance operations or other (conservative) interventions can be attributed to several factors. In general, even newly built constructions often differ notably from the initial graphic works, also following a well-documented project. According to the various cases and to this situation, it is important to implement and improve the existing documentation or to create new documents. In order to describe, manage and analyze a built heritage project appropriately, it is necessary to understand it, so that information in the project can eventually be organized as correct as possible. With this aim, we suggest the procedure that is summarized in Table 1, consisting of a learning phase, a digital reconstruction phase, and a semantic enrichment phase.

Table 1: Summary of the main methodological phases.

Phase	Main actions
Learning phase: *Research and selection of information*	historical pictures; original drawings of the tower from the digital archive of the library of Ghent University (floor plans, elevations, sections); publications in Flemish language (old journal articles); various master thesis; an on-site survey which was documented with a series of photographs, sketches and specific measurements; a literature review of historical documents describing the construction of the tower; existing 2D CAD drawings made available by the responsible university service.
Digital reconstruction phase: *Digital reconstruction in a*	definition of which element build as parametric objects, and in which way; digital reconstruction in Revit of the bearing structures, of the closures and partitions); creation of new classes and families

BIM software	
Semantic Enrichment phase: *Modeling of the ontologies in an ontology editor*	IFC model was converted into an IFC/RDF graph; choice of the basic terms (taxonomy) appropriate for the ontologies; schemes on paper to understand the relations among the technical elements and the new information; definition of the ontologies in TopBraid Composer ontology editor

3.1 Understanding the complexity of the historical built environment

In an initial learning phase, one goes through all kinds of relevant information sources to construct a personal understanding or a mental model of the building. In order to understand a complex system like an existing building/artifact, it helps to break it down into simpler elements and organize this information. We will therefore use a classification scheme.

There are several criteria to classify the technical elements of a building when aiming to support the comprehension and organization of the constructive features. Which criteria are chosen and used depends on the final objective and how the information will be reused. Taking into account purposes like preservation, maintenance, renovation, etc., a functional classification was chosen based on the functions performed by the individual elements. For this reason we chose to take, as general reference, a scheme that meets these requirements, namely the UNI Norms, from the Italian Normative, that define a building as a constructive system. These Norms identify eight (8) different fundamental technological units as follows: structure, closure, internal partition, external partition, plant delivery services, safety system, internal equipment and external equipment (UNI Norm 8289/2, 1981). The UNI Norms have been used by one of the authors in several researches (Di Mascio, 2009 and 2012).

It is necessary to highlight that the UNI Norms are generally used for modern/contemporary residential buildings. Hence, when applying them to historical artifacts and buildings, they need to be adapted or usefully interpreted. For instance, in most modern buildings there is a clear division between bearing structure and closures, in contrast to many historical buildings, in which both functions are performed by the same technical element, e.g. stone wall. Furthermore, many historical buildings present unique technical elements and details. Hence, it is often necessary to customize the classification scheme for each single construction. Despite the amount of structure and objectivity one puts in working with the documents resulting from this survey, it has to be clear that the way in which these documents are interpreted by us shapes how we understand the building and subsequently document it.

3.2 Digital reconstruction

With the term 'digital reconstruction' in Table 1 we refer to a process that foresees the action of building in a virtual environment an existing artifact that belongs to the historical and contemporary heritage of a particular region. Our built heritage is increasingly described, managed and analyzed using information and communication technology (ICT), thereby creating a considerable amount of virtual heritage. As demonstrated in earlier studies (Pauwels et al., 2008, 2009; Di Mascio, 2009, 2012), the usage of ICT instruments and methods in the reconstruction and critical analysis of our built heritage opens up new possibilities in information communication. "*Models not only illustrate what we knew when we started creating them, they also have the potential of revealing new knowledge that was always lurking below the surface of the facts but which, to emerge and be grasped, needed to be visualized in 3D*." (Frischer 2008).

Therefore, the realization of a digital model is not the only purpose. The reconstruction process also contributes to deepen and broaden the knowledge of the artifact. The information gathered and analyzed during the learning phase (section 3.1), together with the knowledge developed during the digital reconstruction phase allow the analysis and disassembly of a historical building, by following a reverse engineering approach, in a 3D modeling environment. The digital reconstruction phase is an interactive process, because, after the analysis and interpretation of the available documentation related to an artifact and during the digital reconstruction itself, the designer can verify the correctness of his interpretations: hence he receives feedback from the model and acts accordingly.

There are various aspects that have to be considered when undertaking a three-dimensional digital reconstruction process of an artifact or building. Some of the most important aspects concern the level of abstraction, the geometry and the organization of the 3D objects belonging to the 3D digital model (Di Mascio, 2012). Different software packages can be used for the 3D digital reconstructions, including, for instance, software for 2D-3D drafting, 3D modeling and building information modeling (BIM). BIM software is mainly used in the design and management of new construction artifacts, but there are some outstanding characteristics of this technology that could be very useful in the documentation, management and analysis of the existing built environment. One of these characteristics is the focus on modeling (parametric) information, rather than mere geometry.

When modeling an (built heritage) artifact in a BIM environment, it is necessary to first determine the class (or family) of the technical elements of the artifact, instead of creating an element such as a window or a pillar only with geometric objects. The affiliation to a specific class defines both the geometric features, which can be fixed or parametric (variable according to the values of some parameters), and a set of relations and norms to control the single parameters. As a result, the model built within a BIM environment will be different from a model realized with any other 3D modeling program. In the latter case, the purpose is often limited to representation or visualization and the objects are only surfaces or geometric solids. In the former case, on the other hand, the virtual model is built including the information that is related to the diverse technical elements (walls, pillars, slabs, doors, windows, etc.). This means that information is associated to each element in order to describe its dimensional, constructive, material and economic features. This results in an information model of the artifact, which can be used for analyses, tests and calculations of various kind. By considering the parametric 3D model, it is possible to automatically generate the traditional 2D graphic works (plans, elevations and sections), in addition to schedules and other output.

3.3 Beyond the static classification: the ontologies

So far, we have considered the building system as something isolated from any other context and unchangeable in time. In reality, each architectural artifact/building is accompanied by a story that starts with its creation and finishes with the end of its use. To be precise, this story could continue also after the end of its use, with the dismissal and recycle or reuse of technical materials or elements ("cradle to cradle"). This story is about the building in all its material and immaterial parts, and about the relationship between the artifact and the environment, built or natural, close or distant. For example, in terms of sustainability it helps to immediate analyze how the artifact is linked with the use of environmental resources. Therefore, in order to represent the memory of a building as such, also useful information from domains outside its initial static classification scheme needs to be represented.

It is evident that a building can be described by a big quantity of heterogeneous data belonging to various knowledge domains. However, linking such data sets together is less evident. Not only different words refer to different meanings or to different information within two disciplines, also identical words often assume very different meanings. These differences also exist between various classification schemes. Hence, this raises the need to communicate and organize data and information among the various domains using a common language. An answer to this practical need has been identified in the knowledge management domain, and in particular in the description and usage of ontologies in this domain. The term ontology, used in the singular form, refers to a field of philosophy (among other things, these are its roots), but there are many other definitions in relation to different contexts. We will refer here to the definition of ontology used in the ICT sector, and in particular in the study of artificial intelligence and knowledge representation, hereby relying on the double definition given by Gruber (1993):

"A specification of a representational vocabulary for a shared domain of discourse — definitions of classes, relations, functions, and other objects — is called an ontology. [...]"

"An ontology is an explicit specification of a conceptualization, [in which a conceptualization is defined as] the objects, concepts, and other entities that are presumed to exist in some area of interest and the relationships that hold them (Genesereth & Nilsson, 1987)."

Therefore, an ontology includes within the same descriptive system both the concepts of a knowledge domain and the relations between these concepts. This way of describing an artifact highlights the relations hidden between various types of information. In this way, many architectural constructions belonging to the historical built environment can be documented and analyzed in innovative ways. It is important to clearly define the usage of an ontology, in addition to the comprehension of its definition (Gruber, 2001). For the creation and the manipulation of ontologies one can rely, for instance, on semantic web technologies (Berners-Lee et al. 2001), which include several standard ontology editors. The ontology editors provide tools to develop ontologies, to visually represent them through graphs, and to test their functionality. The graphic representation of the ontologies is very useful for the understanding of the relations. In a graph, the nodes represent the concepts, while the arches represent their relations. Instances, which are specific examples of information, can represent textual documents, images, bibliographic references, etc. As such, these editors provide the possibility not only to describe and visualize a knowledge domain constituted by classes, properties, instances and relations, but also to link these knowledge domains together explicitly.

4. THE CASE STUDY: THE BOOK TOWER

In our case study, we focused on the tower of the University Library of Ghent, which is also called the Book Tower. The Book Tower (Figure 1) is a famous 20th century building designed by the Belgian architect Henry Van de Velde in 1933, and it is located in the city of Ghent, in Flanders. The tower is 64 meters high, and it is composed of four floors in the basement and twenty floors above ground level. At the top of the tower, there is a panoramic 'belvedere' that overlooks the city at 360°. The floor plan of a standard floor has a squared shape, with three narrow windows on each side. For each floor there are 108 well-pillars. Such a number is justified by the amount and weight of the books on the shelves. For the construction of the tower Van de Velde decided to use reinforced concrete, which was a sign of modernity. The building's value is linked to different aspects: the name of the architect, the materials and the constructive techniques used (innovative at that time), the symbolic value of the building in the skyline of Ghent, where it represents the fourth tower of the city, a tower representing wisdom after the medieval towers of the Belfry, of the Saint Bavo Cathedral and Saint Nicholas' Church, and so forth.

Fig. 1: (left) the tower in its urban fabric pictured from the top of the Belfry; (right) two views of the Book Tower from the street. (Source: personal archive of the authors).

4.1 Constructive characteristics: issues and methodology

To digitally reconstruct the model of the tower in the BIM environment, in this case Revit Architecture, useful information had to be selected among the available information. The original drawings of the Book Tower were collected in the digital library of Ghent. This includes plans, elevations and sections, with varying level of detail. Various dissertations and publications, often in Flemish only, are accompanied by pictures and digital reconstructions, which have helped to understand aspects of the building. These documents also include information about Van de Velde and architectural references useful to comprehend his design choices. After a first vision of these documents, a first inspection of the building was made, with the aim of making a photographic survey.

4.1.1 Digital reconstruction of the Book Tower

During the digital reconstruction phase, it has been essential to document inspections of technical elements and diverse unclear details with pictures, sketches and metrical surveys (Figure 2).

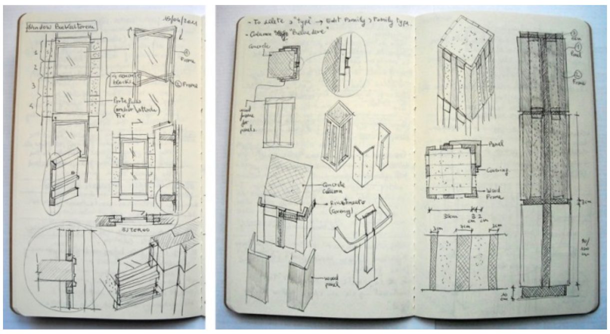


Fig. 2: Preliminary sketches to interpret the technological-constructive system of the windows of the central body of the tower and pillars of the panoramic belvedere.

Because of obvious reasons, certain assumptions had to be made regarding inaccessible areas of the building. However, a careful internal and external examination of the Book Tower has permitted to identify areas where the deteriorated condition of technical elements (i.e. lack of plaster on walls) have shown and hence permitted to document details that were generally hidden (thicknesses and materials). The digital reconstruction phase includes elements belonging to the following classes of technological units: the bearing structures (walls, pillars), the closures (walls, windows) and the internal partitions (walls, shelves). Revit has a classification of *types* and *families* which have their own semantics (parameters and structure). Because most elements of the Book Tower are not standard, it was not possible to adapt the objects in Revit by simply modifying the parameters. Thus it was necessary to create new families and types with their parameters.

4.1.2 The constructive-technological aspects and the definition of the parametric objects

Before starting the modeling phase, it was necessary to identify the elements that have to be considered in the digital reconstruction process and with which level of detail. In general, the UNI Norms have been a reference also to classify the technical elements into specific categories and so to choose in how many parts they should be divided. Questions like the following arose: "in how many parts should the window frame be divided? Should the concrete bricks be modeled, or can we make the approximation of modeling one wall with the added material property 'concrete'?". Answering these questions is essential, because the quality and the kind of information extracted from the model and inserted in schedules, depends on these initial choices. Therefore, it is important to carefully plan the modeling phase.

The first object that has been created was the window that is repeated 12 times in each of the 108 floors of the Tower. The only windows that differ from this standard or typical window are the windows of the basement, which are different in height, and the windows of the belvedere, which have completely different shapes. Before all these windows were modeled, questions like the following were answered in order to plan the modeling phase. Of how many elements is the window composed? What are the fixed and moving parts of the windows? In which direction can the window be opened? How is the frame connected on the wall? Is there a lintel or a sill? Which materials are used? Once these questions were answered, the window has been recreated in Revit as a new family (Figure 3).

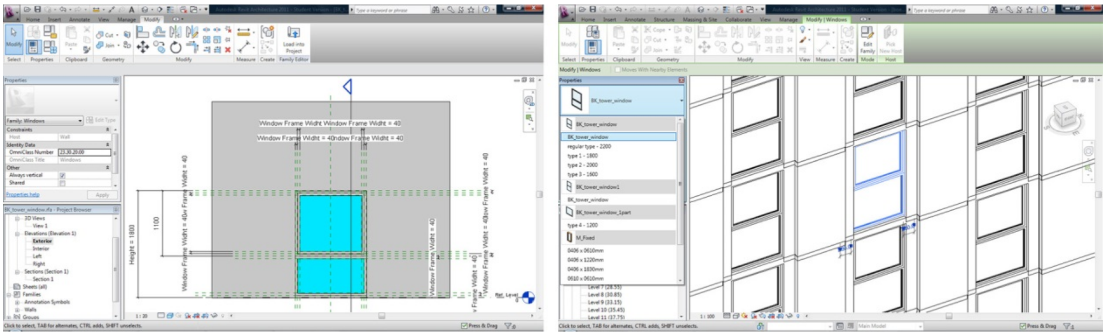


Fig. 3: Creation of a new family for the windows and definition of parameters.

The digital reconstruction of the perimeter walls, in particular the vertically oriented areas close to the windows, was not straightforward. The windows in the facades are bordered by two vertical rows of concrete blocks that continue uninterruptedly from the basement to the top floor. As analyzed and reported on some sketches (see Figure 2), every four blocks of concrete correspond approximately to a window or floor height. The two extremes of these borders coincide with the middle of the inferior and the superior floor. Considering that Revit only allows the insertion of windows inside a wall, a third wall had to be modeled just for inserting these windows. This was the most adequate option considering the available information and tools. For what concerns the representation, this has been an acceptable choice, but on the constructive level the two rows of vertical blocks will appear in the lists of the elements with the same acronym, because they indicate a single wall.

Another interesting technical element is a typical column of the belvedere. The columns are in concrete as the entire bearing structure and they have a wooden panel covering up to a certain height (about 4.30 m). Also in this case a slightly detached panel has allowed the discovery of a supporting wood structure, which would have been impossible to find out in other cases). The wood frame is constituted by vertical and horizontal square sectioned elements, finished by wedged panels with an "L" shape. A new parametric object was created in Revit using different separate solids (Figure 4). A distinct material was assigned to each single solid.

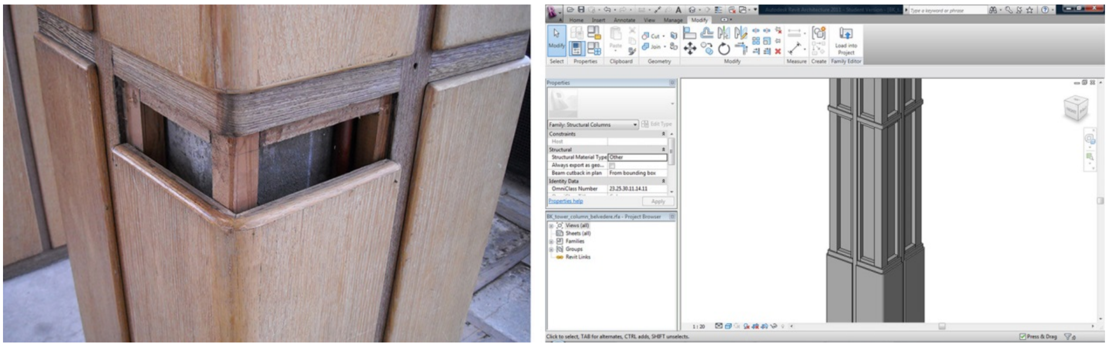


Fig. 4: (left) Picture of a column of the belvedere; (right) a 3D view of the new parametric object of the column.

4.1.3 Generation of schedules

Every technical element in the virtual reconstruction is highlighted by a number and an acronym that identifies a particular category and a particular floor of the tower. The indicative information is assigned even through a grill of invisible vertical floors that defines the position of those objects that belong to the model. In the end this has allowed to automatically obtain several custom schedules, each one with the aim of highlighting and documenting particular characteristics of the artifact.

4.2 Relational characteristics: issues and methodology

4.2.1 Acquisition of the basic documentation and semantic enrichment

The objective of this phase is to enrich the already obtained documentation with additional information of various kinds, organized within an ontology. The BIM model in Revit constitutes the basic information that has to be broadened and enriched with further information. To semantically enrich this BIM model, it is necessary to define one or more knowledge domains and the relations between the classes belonging to each domain. All the ontologies are here considered as part of a central ontology of the tower.

We chose to define six domains, each represented by a distinct ontology with a variable level of detail. For the definition of each ontology, and of the terms to use, we have consulted both online and paper resources. The experimental nature of this research has allowed us to define terms with some degree of freedom, but we tried to build the ontologies so that they can be considered representative at least for a broader audience and for broader common knowledge. The basis of the ontologies has been discussed and defined using paper and pencil, and only in a second step the modeling of ontologies moved towards an ontology editor.

Table 2: The six ontologies that have been defined with the purposes to representing the Book Tower from different points of view.

UNIOntology	the ontology constituted by the classification suggested by the UNI Norm 8290 (September 1981) for the breakdown of the technological system; they provide another classification scheme of the technical elements of the tower, in relation to the scheme used in Revit;
BuildingDesign:	this ontology contains the information about the design of a building (architect, planning references, constructor, etc.);
DocumentationOntology	this ontology describes the available documents (books, images, texts, drawings, video, web sites, etc.);
BuildingDegradation	this ontology describes degradation information (origin of degradation, pathologies of degradation, evolution of the pathologies, change of performances, intervention procedures, guidelines, etc.);
MaterialOntology	this ontology describes material information (constructive materials, raw materials, renewable materials, properties of the materials, etc.);
LocationOntology	this ontology describes geographical locations (countries, regions, cities, villages, etc.).

The BIM model has been exported from Revit into the Industry Foundation Classes (IFC) scheme, which is a standard recently developed in construction industry for describing building information. Second, this IFC model was converted into an IFC/RDF graph using the IFC-to-RDF converter service (UGent Multimedia Lab, 2013). After this step all the information related to the BIM model has been made available in an RDF graph.

For modeling the six other ontologies shown in Table 2, we used the TopBraid Composer ontology editor (Maestro Edition). This ontology editor relies on the Resource Description Framework (RDF) for building graphs. The resulting RDF graphs represent information about the Book Tower and can be understood as directed labeled graphs: a logical AND operator is applied to a range of logical statements containing representations of concepts or objects in the world and their relations. These statements are RDF triples, consisting of a subject, a predicate and an object. Each ontology has a variable level of detail. For instance, the ontology referring to the UNI Norms presents a taxonomic, hierarchical structure, composed by 42 objects that represent classes and subclasses. On the contrary, the ontology location is constituted by 5 objects, among which classes and subclasses. This differentiation is given by different types of information that each ontology represents. The objectives of these ontologies can be synthesized in two main aspects: to enrich the BIM model with new information and to assign to each element a different ontology to improve the information communication between expertise pertaining to other fields. After all classes and properties are modeled, each ontology is populated by a variable number of instances. It is important to remember that instances are concrete examples of information (used documents, materials, etc.). To each instance, one or more properties is assigned, providing different information. For example, an instance of a book has two properties: the first is related to the code that identifies the location of the book in the library; the second refers to the hyperlink of the book sheet available on the website of the University of Ghent Library. Other instances present links to DBpedia which provide general information about specific instances in the building model.

The added value of the ontology not just consists of the possibility of specifying the relations between the classes and consequently also between the instances. The main added value is that all this information can be made publicly available to a wide audience, in a language (RDF) that can be understood by the systems that they use, so that this wider audience can reuse this information in other contexts (including building maintenance or restoration projects). In order to query the ontology in an efficient way, it is necessary to create a widespread network of relations between the instances. This is a procedure that allows a better description of the building. All ontologies are connected to create a single description of the Book Tower; the central ontology of the building was named *Building Ontology*. Through the option *HTML generator*, the whole ontology has been exported and it could be consulted as a web site, through hyperlinks.

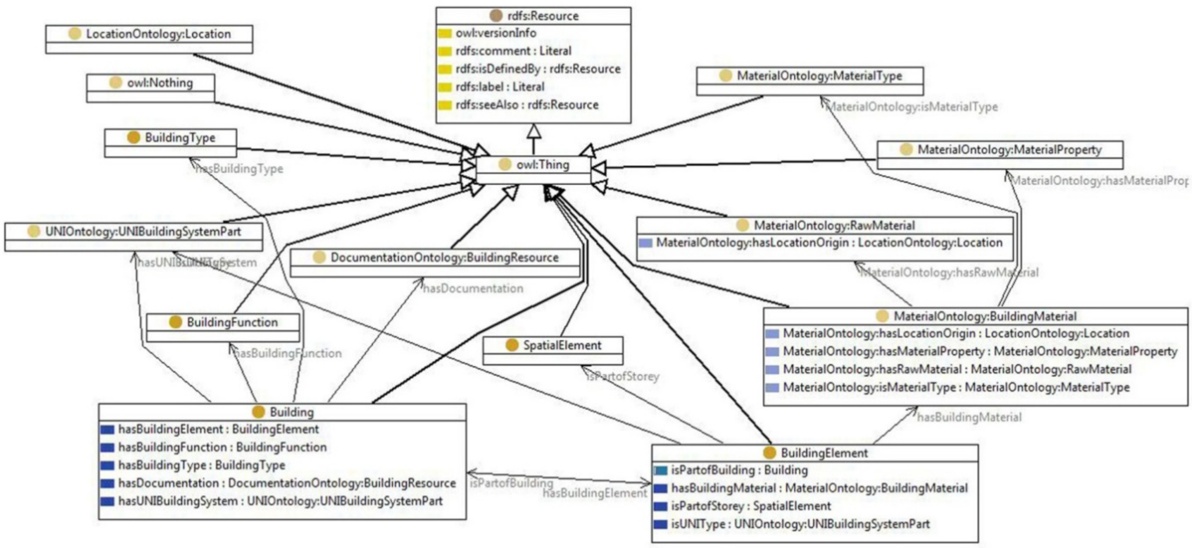


Fig. 5: Diagram of the relations, within the *Building Ontology*, among the classes belonging to the single ontologies.

5. DISCUSSION OF THE RESULTS

A digital model has been built in a BIM environment for analyzing the constructive characteristics of the Book Tower. This model allows to manage the high number of technical elements of the tower which are repeated in each floor, and to create tables with various information (dimensional, material, etc.), useful to manage a maintenance plan. The digital reconstruction of the Book Tower has arisen some reflections concerning the use of BIM software for the documentation of existing artifacts. In order to realize a BIM model, one needs to take care of the way in which the geometric and constructive aspects are modeled. In the BIM model, the technical elements and their constructive relations need to be clearly defined. For example, it is necessary to avoid mistakes like the penetration of solids that represent serious constructive mistakes. The quality of the modeling depends both on a correct understanding/interpretation of the constructive system of the real building/artifact, and from a correct use of the methods and tools in the BIM environment. This is not different from the way in which any other 3D modeling package should be used.

The use of ontologies has allowed to enrich the BIM model with information that documents the aspects linked both to the life cycle of an artifact and its cultural features. By linking the BIM model to the UNI Norms classifications in the TopBraid ontology editor, it has also been possible to provide an additional terminological interpretation of the constructive system of the Book Tower. As a result, the technical elements of the Book Tower can be read either according to the Revit ontology or according to the UNI Norms ontology. In this way it widens the communicability of the information.

Both the digital modeling and the semantic enrichment phase of the considered digital heritage project confirmed how essential a careful initial planning phase is. It is necessary to carefully define the objectives that one wants to reach. From this information it is possible to choose an adequate terminology and taxonomy. There are diverse interpretations through which an artifact can be represented and the creation process on such representations always is an iterative process that is characterized by continuous adjustments.

6. CONCLUSIONS

In this paper we have elaborated and proposed a methodological path (in detail: a theoretical framework, methods and tools) to improve the comprehension and documentation of buildings/artifacts pertaining to the historical built environment. The BIM modeling environment proved to be a tool fit for the digital reconstruction and management of the constructive characteristics of a building pertaining to the historical built environment. Some features of the BIM modeling environment are obviously created for new constructions, which could result in some difficulties regarding the reconstruction of constructive and formal nonstandard solutions (e.g. window sidings of the Book Tower). But in general, BIM modeling environments prove to be relevant for the digital reconstruction of buildings belonging to the historical built heritage. Through the digital three-dimensional model it is possible to make further analyses, like the ones related to energy and structural aspects; it is possible to design and manage renovation and requalification interventions, in order to save time and economic and material resources; and so forth.

The elaboration of specific ontologies and their connection and representation using ontology editors allows to understand, visualize and communicate heterogeneous information linked to the studies artifact. Through this network of relations it is possible to rebuild the links with the place of the building, with the experts that have worked for its construction, with cultural references to those elements that have influenced the design and constructive choices, with the origin of the materials and of the technical elements, with the available documentation related to the building and its technical elements, and so forth. Once this complex network of relations has been built, it is possible to use it in preservation and maintenance actions. These actions can consequently take into consideration the functional aspects as well as the cultural value of the artifact/building and of aspects linked to the sustainability.

Both the three-dimensional model and the ontologies contribute to improve the dialogue among domain experts and professionals who collaborate during the maintenance, preservation and renovation processes. The shared conceptualization represented by this model and the ontologies allows domain experts with various aims to clearly interpret and use the represented information for their purposes. Of course, in specific (maintenance or preservation) projects, the decisions still need to be coordinated by a central figure, for example an architect, in order to reach a well-defined general objective. The instruments and methods outlined in this paper can of course be used in real world built heritage projects, but, with the adequate adjustments, it can be applicable also to other projects and objectives. One such objective can be the diffusion of heritage information in real and virtual museums for cultural purposes. The Finnish CultureSampo platform (Hyvönen et al. 2009) is a recent example of such a semantic cultural heritage platform. Other objectives can also be targeted, simply because semantic web technologies allow to widely spread knowledge to interested parties, while also enabling these interested parties to understand the meaning of this information.

7. ACKNOWLEDGMENTS

We would like to thank the people from the Book Tower for making the information available.

8. REFERENCES

Berners-Lee, T., Hendler, J., and Lassila, O. (2001) The semantic web. Scientific American 284, 5, 35–43.

Di Mascio, D. (2009) Digital Reconstruction and Analysis of Turchinio's Trabocco: A method of digital reconstruction of a complex structure as a way to improve our knowledge of a cultural heritage artifact, Digitizing Architecture: Formalization and Content, in 4th International Conference Proceedings of the Arab Society for Computer Aided Architectural Design (ASCAAD 2009), Manama, Kingdom of Bahrain, 11-12 May 2009, pp. 177-189.

Di Mascio, D. (2012) ICT in the knowledge and in the documentation of the peculiarities of the historical and contemporary built environment. Methodological paths and case studies, PhD thesis, Scuola Superiore "G. d'Annunzio" School of Advanced Studies, G..d'Annunzio University, Chieti-Pescara, Italy.

Frischer, B. (2008) The Rome Reborn Project. How Technology is helping us to study history, OpEd, November 10, 2008. University of Virginia,
<http://www.romereborn.virginia.edu/rome_reborn_2_documents/papers/Frischer_OpEd_final2.pdf>
(last accessed on 12 May 2013).

Genesereth, M. R., & Nilsson, N. J. (1987) Logical Foundations of Artificial Intelligence. San Mateo, CA: Morgan Kaufmann Publishers.

Gruber, T. (1993) A translation approach to portable ontology specifications. Knowledge Acquisition 5(2), 199-220.

Gruber, T. (2001) What is an Ontology? Stanford: Knowledge Systems Laboratory. Stanford University, <http://www-ksl.stanford.edu/kst/what-is-an-ontology.html> (last accessed on 16 May 2013).

Heine, E. (1999) High precision building documentation: element definition and data structuring, Proceedings of the ICOMOS & ISPRS Committee for the Documentation of Cultural Heritage, Working Group II (Ed.): Mapping and Preservation for the New Millenium - Brazil 500 year. Recife/Brazil.

Hyvönen, E., Mäkelä, E., Kauppinen, T., Alm, O., Kurki, J., Ruotsalo, T., Seppälä, K., Takala, J., Puputti, K., Kuittinen, H., Viljanen, K., TUominen, J., Palonen, T., Frosterus, M., Sinkkilä , R., Paakkarinen, P., Laitio, J., and Nyberg, K. (2009) CultureSampo - Finnish cultural heritage collections on the semantic web 2.0, in Proceedings of the 1st International Symposium on Digital Humanities for Japanese Arts and Cultures.

Martens, B., Peter, H. (2002) Developing Systematics Regarding Virtual Reconstruction of Synagogues, Thresholds - Design, Research, Education and Practice, in the Space Between the Physical and the Virtual, in Proceedings of the 2002 Annual Conference of the Association for Computer Aided Design In Architecture, Pomona (California) 24-27 October 2002, pp. 349-356.

Maver, T., Petric, J. (1999) Virtual Heritage: Is There a Future for the Past? III Congreso Iberoamericano de Grafico Digital, in SIGRADI Conference Proceedings, Montevideo (Uruguay) September 29th - October 1st 1999, pp. 482-487.

Pauwels, P., Verstraeten, R., De Meyer, R., Van Campenhout, J. (2008) Architectural information modeling for virtual heritage application, in Proceedings of the 14th International Conference on Virtual Systems and Multimedia, pp. 18-23.

Pauwels, P., Verstraeten, R., De Meyer, R., Van Campenhout, J. (2009) Architectural information modeling in construction history, in Proceedings of the Third International Congress on Construction History, pp. 1139-1149.

UGent MultiMediaLab, "IFC-to-RDF Converter Service" (2013) Available online:
<http://demo.mmlab.be/IFC-repo/> (last accessed 8 July 2013)

UNI Norm 8289/2 (1981) Residential building. Building elements. Analysis of requirements, June 1981.

PILOT TESTS OF AUGMENTED REALITIES IN SCIENCE DISPLAYS AND DESIGN PRESENTATIONS[1]

Syed Huzaifah Syed Omar, Puteri Shireen Jahnkassim & Murni Mahmud
International Islamic University, Malaysia

ABSTRACT: *Augmented Reality (AR) enriches the education environment by adding spatially aligned virtual objects (3D models, 2D textures, textual annotations, etc.) by means of special display technologies .This research was a pilot test within a longer research project aimed at investigating and evaluating the relevance of realism elements in 3d AR education technologies in science centers and design presentations. The main advantages of using virtual objects are that they can be animated, they are interactive and can respond to the user's actions and are not constrained by the costs and practical or physical limitations of real objects. These factors make AR a powerful educational tool. In this research, AR Planets and AR Dinosaur in National Science Center Malaysia were developed as a testbed. A pilot study - to gauge the public reaction to the technology - was developed involving the augmenting of earth globe and a dinosaur. Researchers found out that both adult and children reactions were enthusiastic, changing a dry subject such as science to an exciting activity. A survey was undertaken to gauge the reactions and significance to aspects of realism in AR. User studies were done using field studies to study the effectiveness of realism in AR application in real scenarios. The participants were asked to evaluate two different approaches of application to experience the Augmented 3d science content with heavy realism content and less realism content. After a couple of minutes exploring the content with recorded video, they filled in the questionnaire which assessed their experience towards the application. The importance to the realism elements recorded with the feedback and attitude by the users such as their satisfaction and feel real to the AR content and the feeling of connection to the content elements .The evaluation found out that 98% of the participants believe the AR content with heavy realism elements is superior to compare with AR content with less realism elements in science center. This research will give a better guidance to education centers on user expectations and responses towards such an application including the importance and significance on using realism in Augmented Reality application.*

KEYWORDS: *Augmented reality, education, science, design, presentation, science center, planet, dinosaur*

1. INTRODUCTION

This paper presents two prototype developments – Dinosaur AR for National Science Center, Malaysia and 3D Interior building AR for ALM Builders Company. We investigated methods to have an optimized realistic animated AR content for interior building design presentation that commonly involve details 3D drawing With these methods allow the AR content augmented or pop up from marker tracking paper with more immersive. The result of the study indicated that this development can provide a quality approach in AR evaluation, more 'presence' information for attraction and hence will give the real experience and knowledge to the users. Having the benefits of this development will facilitate and expedite the construction process simulation as well as heavy 3D AR development cost for the AR science display and AR presentation in augmented reality.

Evaluation and pilot tests regarding the introduction of mobile guides in the museum setting is a concrete issue that has hopefully and unlike other areas in human interaction has been accredited sufficient interest and important among related scientific community (Kelly,2002). The design, implementation and maintenance of an augmented realities display and presentation for science need to be systematically and creatively designed based on the result of pilot test and surveys.

[1] Citation: Omar, S. H. S., Kassim, P. S. J. & Mahmud, M. (2013). Pilot tests of augmented realities in science displays and design presentations. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

2. AUGMENTED REALITY IN SCIENCE AND EDUCATION

There are 2 types of AR application for science and education content: 1) location-aware; and 2) vision-based. Location-aware AR presents digital media to learners as they move through a physical area with a GPS-enabled smart phone or similar mobile device The media (i.e., text, graphics, audio, video, 3D models) augment the physical environment with narrative, navigation, and/or academic information relevant to the location. In contrast, vision-based AR presents digital media to learners after they point the camera in their mobile device at an object**.**

The potential power of AR as a learning tool is its ability “to enable students to see the world around them in new ways and engage with realistic issues in a context with which the students are already connected” (Klopfer & Sheldon, 2010, p. 86). These two types of AR influence several smart phone capabilities (i.e., GPS, camera, object recognition and tracking) to create “immersive” learning experiences within the physical environment, providing educators with a novel and potentially transformative tool for teaching and learning (Azuma, Baillot, Behringer, Feiner, Julier, & MacIntyre, 2001; Dede, 2009; Johnson, Smith, Willis, Levine, & Haywood, 2011).

Fig. 1: Crowd enjoying the AR Dinosaur content in National Science Center

Studies have shown that the element of presence and immersion in a digital and real environment can enhance education in at least three ways: by allowing multiple perspectives, situated learning, and transfer.

Moreover, these two forms of AR both leverage the affordance of context sensitivity, which enables the mobile device to “know” where it is in the physical world and to present digital content to the user that is relevant to that location (Klopfer, Squire, & Chapter 67: Augmented reality Jenkins, 2002). For example, using the medium of sensorily immersive virtual reality, Project ScienceSpace contrasted egocentric rather than exocentric frames of reference (Salzman, Dede, Loftin, & Chen, 2009).

3. RELATED WORK

3.1 Science Center To Go (Scetgo)

The “Science Center To Go” (SCeTGo) approach aims at the presentation of such AR technology initiative in science teaching both in formal & informal educational environments that facilitates lifelong learning by offering to learners the opportunity to gain exposure to everyday science in a way that is appropriate to the individual level of understanding.

SCeTGo's approach is based on an educational kit that is delivered in the form of a small suit- case and contains a tablet, a web camera, a series of 3-D printed miniatures and a user guide. This hardware combined in various arrangements can form in total five mini- exhibits that illustrate various physical phenomena linked to secondary school curricular: sound wave propagation, rigid body (double cone) motion on an inclined plane, wing dynamics, wave-particle duality and gas particles' velocity distribution. Learners can interact dynamically with the miniature exhibits and by using AR enrich their optical view with information relevant to the physical content shown. Some of the examples of the content include explanation of why do planes fly and why does the siren sound of a fire truck is different when it approaches a n observer than when it moves away from him. (Angelos Lazoudis, The science center to go project, EDEN - 2011 Open Classroom Conference)

3.2 Science Stories" Augmented Reality Science Museum Tour App

Fig. 2: James May "Science Stories" augmented reality Science Museum tour app (HANDS-ON: James May "Science Stories" augmented reality science museum tour app.
- http://www.techdigest.tv/2012/04/hands-on_james.html)

3.3 AR London Museum

Another AR application that relate with science center is Science Stories AR London Science Museum tour app. Using smartphone and tablet, user can click on a marker at selected plinths (refer figure 3), a 3D walking talking rendering of James May appears magically on screen to talk to the user through the objects, how they work and their place in history. The talking and walking fully in 3D object which user can move around freely as long as the plinth trigger marking stays in view of the camera sensor. The app also has an “At Home” mode to let user access the avatar of James May commentary outside of the museum.

Street Museum is an augmented reality iPhone app created by the Museum of London that allows you to browse historical photographs in various parts of the city. The app leads you to various locations around London using either the map or GPS. Once you’re there, click the “3D View” button, and the app will recognize the location and overlay the historical photograph over the live video feed of the real world, giving you a brief glimpse into how the past looked. The application uses LAYAR based apps to create a layer of image based on geo location marker.

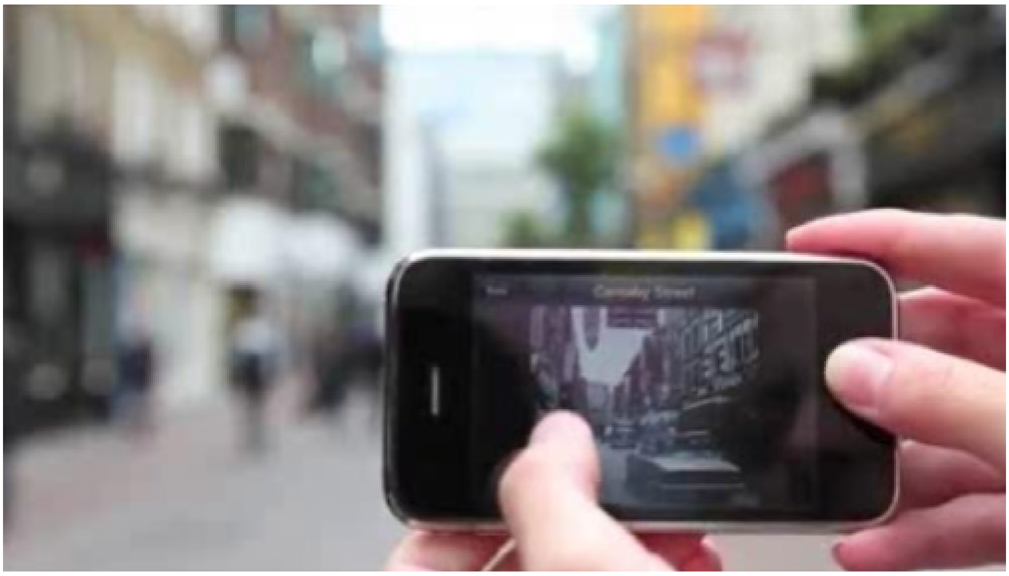


Fig. 3: Using smartphone to run Augmented Reality App for London Street Museum
(http://attention2ads.com/post/2797866923/taking-arts-to-the-streeds-the-street-museum-app-from)

3.4 Augmented Reality (AR) Magnet

Augmented Reality (AR) Magnet displayed in the Fleet's exhibit gallery was intended to visualize how the magnetic field works. The new AR application exhibit, the first of its kind in a Balboa Park museum, serves as a

pilot project to investigate the usefulness of mobile apps as teaching tools to enhance hands-on exhibits in informal science educational institutes like the Reuben H. Fleet Science Center. The app has been custom built using Qualcomm's AR technology, for the Fleet as part of an interactive exhibit on magnets and magnetism.

Fig. 4: The magnetic field visualized using Augmented Reality application
(http://www.youtube.com/watch?v=GiJjTdoWZFs)

4. METHODOLOGY

This paper was aimed at investigating evaluate the relevance of using Augmented Reality in science display and design presentation in the optimized 3d animated content. User studies are done using field studies to study the effectiveness of this application in real scenarios. The participants will be experience the AR Dinosaur in National Science center. After a couple of minutes of exploring the content with recorded video, they will fill in the questionnaire on their experience towards the system. The importance to the presence elements will be recorded with the feedback and the attitude of the users such as their satisfaction and feel real to the 3d AR content, the feeling of connection to the content elements and how comfortable the system are . The participants will evaluate whether they deem the presence content as suitable for museum and improvement for the current content and whether they would be willing to pay a higher entrance fee, and whether they prefer to go to the science display booth to experience the new technology with heavy presence elements. All items will be answered on the questionnaire.

5. USER TASK ANALYSIS

The aim of task analysis in this paper is to classify a complete description of tasks and actions required to use an application system development as well as other resources necessary for the user and the system to cooperatively perform tasks (Hix & Hartson, 1993). Generic user requirements were identified during our preliminary study in order to perform the analysis using face-to-face interviews with science visitors (Murni et al., 2009) and a series of roundtable discussions with content expert.

National Science Center has granted a space to locate a booth to do pilot test of Augmented Reality Science Display during their Science Festival 2012. A simple booth has been designed with LED 40 inch, webcam and CPU experimenting Dinosaur content for various respondents.

Following are notable findings from this preliminary study:

The demographic information of 100 respondents shows computer competency of majority respondents is intermediate (66% valid percent), novice (24%), expert (6 %), and not exposed (4 %). However, majority (94%) are not exposed to Augmented Reality while 6% familiar with the term Augmented Reality.

There are 100 participants: 56 male, 44 female, and majority (64%) of them are below 20 years old involved in this study. It is observed that teenagers and kids were enthusiastic to explore the 3D AR application rather than adults. In most cases, when they were accompanied by parents, their parents normally asked the children to participate while the parents observed or guided them in nearby area.

6. USABILITY EVALUATION

Table 2 describes the results gathered using usability questionnaire. Respondents were satisfied that overall our AR Dinosaur application provides sense of presence (86%). This application also provides satisfactory learning experience (91) and satisfactory overall usability (89).

Table 2: Usability evaluation

Item	Evaluation	Percentage (Agree)
1	I felt a sense of being immersed in the augmented environment	77
2	I did not need to feel immersed in the virtual environment to complete my task	23
3	I got a sense of presence (i.e. communicate with dinosaur)	85
4	The quality of 3D content reduced my feeling of presence	43
5	The display resolution reduced my sense of presence	46
6	I felt isolated and not part of the virtual environment	13
7	I had a good sense of scale in the virtual environment	74
8	I thought the system provides a good learning experience	8
9	The system improves my learning capability	72
10	I can easily recognize elements/content shown in this application	100
11	I would be comfortable using this system for long periods	88
12	I did not have a clear idea of how to perform a particular task	6
13	I found it difficult to learn how to use the system	2
14	I felt in control of the system	72
15	The system did not work as expected	11
16	I found it difficult to work with the system	24
17	I enjoyed working with the system	94

6.1 AR Science Display Crowds:

The AR Dinosaur received extremely high numbers of visitors and crowd visited the booth and experienced the contents. In total, the booth received at least ‘3424’ numbers of visits during the events and each of visits spent at least ‘4 minutes’ to play with the AR contents.

Table 3: AR booth; visits & time consumed with AR application statistics

Date/Day	Visits (No.)	Time Consumed (Min.)
11/12/12 Tuesday	719	2876
12/12/12 Wednesday	473	1892
13/12/12 Thursday	457	1828
14/12/12 Friday	414	1656
15/12/12 Saturday	628	2512
16/12/12 Sunday	733	2932
Total	3424	13696

6.1.1 Attractions

The animated AR dinosaur became one of the reasons for visitors to stop by and look at the AR Application. The visitors fascinated with the 3D dinosaur that looks like standing together with them in the LED tv screen. The webcam also attracted most kids as they can see themselves in the screen while playing with the content. The kids tend to stay longer in front of the screen as they like to explore more on the AR earth and dinosaur beside the camera on the top of screen can exactly view their faces together with AR model. The camera position also suit with kid's height.

The adult visitors also attract with the AR model by the kids reaction towards it on screen and join together to snap some pictures. Besides, some of the visitors amazingly enhanced the interactivity of AR application with people by taking picture of marker with their own smartphone, tablet and make the AR model appears on their phone/tablet screen. The string attached to marker board help visitors to get the proper length to view the AR model, besides preventing the board from been taken away.

The markers that have been designed also suit with kids and adults hand thus give them better and proper position to hold. The utmost important reason for high numbers of crowd was because the booth location at the center area thanks to PSN. The best thing about AR booth was when parents can capture photos of their kids holding a dinosaur and earth and to be shared with others.

6.1.2 Issues

Most of the time, the lighting factor became one of the reasons for AR model not to appear properly. Although the location was perfect to attract people, but the lighting inside the hall was not consistent. It created confusion to the camera and need to be adjusted from time to time.

The camera position is not suitable with adults' height. The adult visitor still can view the AR model with kid's height focus camera, but most of them tend to duck down to let their faces also appeared on the screen together with AR model.

The marker board on the floor always been stomped by visitors as they think it is one of the required action to make the AR dinosaur appear. Need to put direction together on the floor afterward. Some kids really put emotions on the content and as a result they tried to hold and punch the dinosaur at the screen and webcam.

6.1.3 Future Plans for Improvement.

More screen need to be added. With only one screen definitely cannot entertain all the crowd that combined kids, teenagers, and adults that usually come in a form of student groups and families.

A holder stand needs to be prepared afterward for marker board, as it is more proper than just using a chair to display the marker board.

The limit line for viewing should be put on the floor to avoid the AR model disappeared due to marker out of camera focus, besides avoiding the kids to slam on the screen again.

Need to put direction together on the floor afterward.

Need to buy better software that has better marker detection although the lighting is not consistent. The current software can still be used for experiments, demo and presentation.

By participated in Science Festival 2012 organized by National Science Center, a lot of strengths and weaknesses can be reviewed to improve the AR content. The AR Dinosaur application also manages to attract crowds and get highly positive feedbacks from them. From the festival, much potential can be seen for AR science display in the future.

In general, visitors would like to have some interactive exhibits in the science center in order to learn and experience science and education content. Those in family trips would be relieved to see their children enjoy the 3D AR content by experiencing and experimenting things by their own. This contributes to the design requirements of the AR application.

6.2 3D AR Interior Building Content

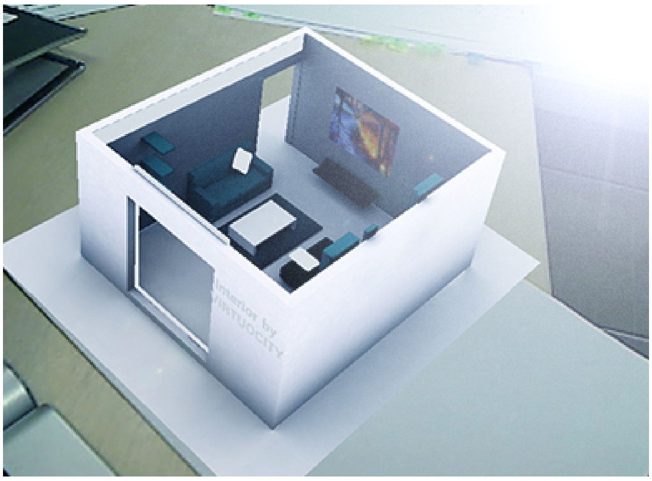


Fig. 5: 3D AR interior building content presented to ALM Builders.

To get perspective of AR content using design presentation, an application has been presented to a company named ALM Builders. ALM Builders is an architect company, seek a new style of presentation for their new marketing strategy. Series of discussion has been conducted with the members of company and an AR application has been designed to build a 3D interior building content. This AR content will replace their old way of presenting new building to customer. A realistic and animated AR prototype was presented to the expert of ALM Builders and the expert made comments during the presentation. Finally, a set of requirements was established where among others: the AR application should be able to cater more customers and visitors at their booth. The booth design and the content also will replace their small scale building mockup and can be placed anywhere and anytime they want .The AR content also should be intuitive and easy to use by the general public; and it can support social interaction that may initiate conversation among family members or groups.

6.2.1 Expert Review

Expert review and feedback of the application was really good and positive. At the early stage, the expert list out requirements to build the AR application content. The requirements are:

1) Easy to transfer from any location

2) Can easily attract visitors and customers

3) Low cost

4) Easy maintenance

Based on these requirements, the AR prototype develops by using high detail 3d content of an interior building model. The 3d model exported to AR application with some animation features to impress the visitors.

6.2.2 Feedback and Recommendations

During the first expert review, the AR interior building prototype as shown in Figure 4 was presented in front of an architect group. One of the architects questioned the inconsistency to control the prototype as it depends on the lighting condition. Therefore, the prototype hardware and software need to be improved to make sure that they manage to control the experience the prototype seamlessly. Aside from that, all architects in the group agree that the prototype meets the entire requirement given.

7. PROCEDURE

During the presentation, at least three evaluators were there, one was to respond to respondents‟ enquiries and another was to mark time stamps and did the video recording, and both observed the respondents and gathered other qualitative data such as respondents‟ expressions and conversations if they did the session in pairs or in groups. In most cases, respondents were free to play with the AR content and complete predesigned tasks themselves. Evaluators would help them only upon request and at critical incidents that halted respondents to complete their tasks

8. PICTURES DURING PILOT TEST

These are several other pictures that have been captured during the pilot test.


A.R.
DINOSAUR
A.R.
EARTH


A.R.
DINOSAUR
A.R.
EARTH
EARTH


A.R.
DINOSAUR
A.R.
EARTH
EARTH

9. DISCUSSION

The key aim of this study was to investigate the important elements of presence in Augmented Reality, similar to the study by Lombard and Ditton (1997) whether presence in media is necessarily a good thing or not as significant as expected, especially in science displays and design presentations. Based on the deliberations above clearly the objectives have been achieved to focus on the technical challenges and requirements, particularly on the presence elements for AR visualization to represent education and building content for science displays and design presentation. The aim to introduce a new method of optimizing and to add realism elements to the content within innovative uses of Augmented Reality also attained. Having the benefits from this development will facilitate and expedite the construction process simulation as well as heavy 3D AR development costs for the science displays and design presentation.

As a conclusion, the pilot test on evaluating presence in Augmented Reality for cultural heritage help us answer some of the important questions raised by cultural heritage researcher and technology developers. Can presence improve Augmented Reality content for science displays and design presentations significantly? Or is it just an add-on to the content? Is presence efficient for all project types? Can a content developer easily implement presence in their application and is it worth the cost and the budget? Will presence bring fun and attract people with education and building content? And will presence give impact to the future generation? Overall the survey found a significant number of percentages of satisfactory overall usability by 89% respondents proved that by applying presence elements in Augmented Reality for science displays and design presentation was significant and provided more benefits and fun experience to the users and visitors.

10. REFERENCES

Barfield, W. Sheridan, T., Zeltzer, D. and Slater, M. *"Presence and Performance Within Virtual Environments"* W. Barfield and T. Furness (eds) Virtual Environments and Advanced Interface Design, Oxford University Press. 1995

Chen, C.T., and T.W. Chang. *"1:1 Spatially Augmented Reality Design Environment."* Innovations in Design & Decision Support Systems in Architecture and Urban Planning,

Daniel Wagner*, "Handheld Augmented Reality".* Graz University of Technology Austria, 2007

Dede, C. *Augmented Reality Technology Brings Learning to Life*. 2009 27.05.2010]; Available from: http://www.gse.harvard.edu/blog/uk/2009/09/augmented-reality-technology-brings-learning-to-life.html.

Dr. Rer. Nat. *"Real-Time Non-Photorealistic Rendering Techniques For Illustrating 3d Scenes and Their Dynamics"* , 2005

Lukasz Piwowar. *"Voxel Method for Realistic Rendering"*, University Of Wroc Law, Wroc Law, Poland September 2008

Robinett, W. *"Synthetic Experience: A Taxonomy."* Presence: Teleoperators and Virtual Environments, 1(2), Summer 1992

SHaibu b Garba. *"Virtual Reality Implementation In The Architecture Curricullum*. , 2004

Slater, M. and Usoh, M. (1993) *Presence in Immersive Virtual Environments, Proceedings of the IEEE Conference* - Virtual Reality Annual International Symposium, IEEE Neural Networks Council, Seattle, WA (September, 1993), 90-96.

Stricker, D., Dähne, P., Seibert, F., Christou, I., Almeida, L., Ioannidis, N.: *Design and Development Issues for ARCHEOGUIDE:* An Augmented Reality-based Cultural Heritage On-site Guide. In: EuroImage ICAV 3DConference in Augmented Virtual Environments and Three-dimensional Imaging, Mykonos, Greece , 2001

Witmer & Singer. *"Measuring Presence in Virtual Environments: A Presence Questionnaire"* . 1998
Papagiannakis, G., Ponder, M., Molet, T., Kshirsagar, S., Cordier, F., Magnenat-Thalmann, N., Thalmann, D.: LIFEPLUS: Revival of life in ancient Pompeii. In: Virtual Systems and Multimedia, VSMM 2002 (2002) 15. Papagiannakis, G., Schertenleib, S., O'Kennedy,

THE IMPORTANCE OF ENGAGING ENGINEERING AND CONSTRUCTION LEARNERS IN VIRTUAL WORLDS AND SERIOUS GAMES

Angela Addison, William T. O'Hare, Mohamad Kassem & Nashwan Dawood
Teesside University

ABSTRACT: *The engineering and construction industries require their workforce to undertake complex learning and training activities. Exposing new employees, graduates, or apprentices to these environments could endanger their safety and the safety of those working with them. On site education and training also requires an investment of time from skilled individuals and companies. Problems accessing environments, such as construction sites, heavy plants or chemical manufacturers, are substantially heightened by the need to risk assess and comply with Health and Safety legislation making the traditional "hands on" and "shadowing" approaches to training and education more complicated than in the past. These difficulties are also compounded by changes to the geographical locations (e.g. distance learning, on site) of those studying to join these career paths or progress within them. Therefore, educational institutions and trainers must consider how to deliver this skill based learning for both those with access to academic premises and those learning at a distance. New technologies such as serious games are one of the solutions being explored.*

This paper undertakes an analysis of safety issues and safety training and learning methods relating to the construction industry. The paper takes its start point from a Health and Safety Executive commissioned report in 2003 (Hide et al, 2003) and questions if sufficient improvements in safety have been achieved within the construction industry since its publication. Then, the paper investigates the development of education and training that meets the necessary reality and complexity of engineering and construction sectors and the ability of serious games to provide timely and accessible training to achieve competency within these sectors.

KEYWORDS: *Competency, learning, safety, serious games, training, virtual worlds*

1. INTRODUCTION

The environments in which engineering and construction industry personnel operate require high levels of competency to prevent potentially devastating incidents and accidents, or even to cause widespread harm to the surrounding population (Anderson, 2007). Hide et al (2003), suggested that safety in the construction industry was of increasing concern as accidents within this sector were not only increasing in numbers, but also in severity. More recent data suggests that, although there has been a decrease in fatal injuries, this decline may, in part, be due a decrease in activity associated with the economic downturn (Bureau of Labor Statistics, 2011) and that incidents are still more common, per workforce representation, in construction than in other industries (Health and Safety Executive, 2011). This appears to reflect the international trend (Fang & Wu, 2013).

Most (70%) construction accidents were caused by human factors associated with employees' actions, behavioural traits and competency (Hide et al., 2003). Lack of Personal Protective Equipment (PPE), inadequate PPE, or a failure to use PPE correctly were common factors; PPE can only be effective if it is supplied and used correctly by the workforce (Lombardi et al., 2005). Hide et al. (2003) also identified factors such as travel around the construction site, employee actions and poor team communication as common causes. It has been suggested that the inclusion of an increased number of migrant workers lead to problems with effective communication (Bust et al, 2008) although a study in Canada also suggested that the risk is higher among immigrants whose education exceeds that of job requirements compared with other immigrants (Premji & Smith, 2012).

Hide et al. (2003) also considered other causes, such as failure of the materials and equipment used by employees and poor site design and layout. The design of the construction site was also one of the fundamental areas identified as being responsible for injuries to workers considered by Toole (2002) and by Rajendran & Gambatese

Citation: Addison, A., O'Hare, W. T., Kassem, M. & Dawood, N. (2013). The importance of engaging engineering and construction learners in virtual worlds and serious games. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

(2009). The boundaries and access points should provide safe egress for construction employees; however, as members of the general public may come into close contact with the site entrance they are also at risk and must be taken into account (Sawacha et al, 1999).

1.1 Training and learning methods

All of the factors considered above have some human component, either in employer responsibilities or employee actions. Training is often seen as an effective way to improve behaviors and, sometimes, attitudes, although behavior and working patterns of individuals are influenced by many factors, including the central beliefs and attitudes of each individual and the social norms experienced by individuals (Lapinsky et al, 2005; Parker, 2006; Young, 2007). Training endeavors to impart knowledge, skills and attitudes necessary to perform job-related tasks (Truelove, 1992: 273). Learning is generally defined more holistically as a process that encompasses both training and education (Jensen, 2001) with training seen as 'learning by doing' and education as 'learning by thinking' (Garavan, 1997: 42). Training is defined as learning that is provided in order to improve performance on the present job (Nadler, 1984). Active training is defined as instructional activities involving learners in doing things and thinking about what they are doing (Bonwell & Eison, 1991) and as a form of learning in which the learner uses opportunities to decide about aspects of the learning process or as the extent to which the learner is challenged to use his or her mental abilities while learning (VeldhuisDiermanse, 2002). Proponents of active learning share an underlying assumption that the learner is self-reflective and actively engaged as a participant in his or her interactions with the world (Sarason and Banbury, 2004). Passive training is form of training in which learners do not receive a feedback (Rae, 1995). Examples of passive training methods are videos, lectures or any classroom-style training methods without feedback. An overview of the different training methods is reported in figure 1. The ability of such techniques to meet the reality and complexity of engineering and construction contexts is discussed in the following sections using an extensive literature review.

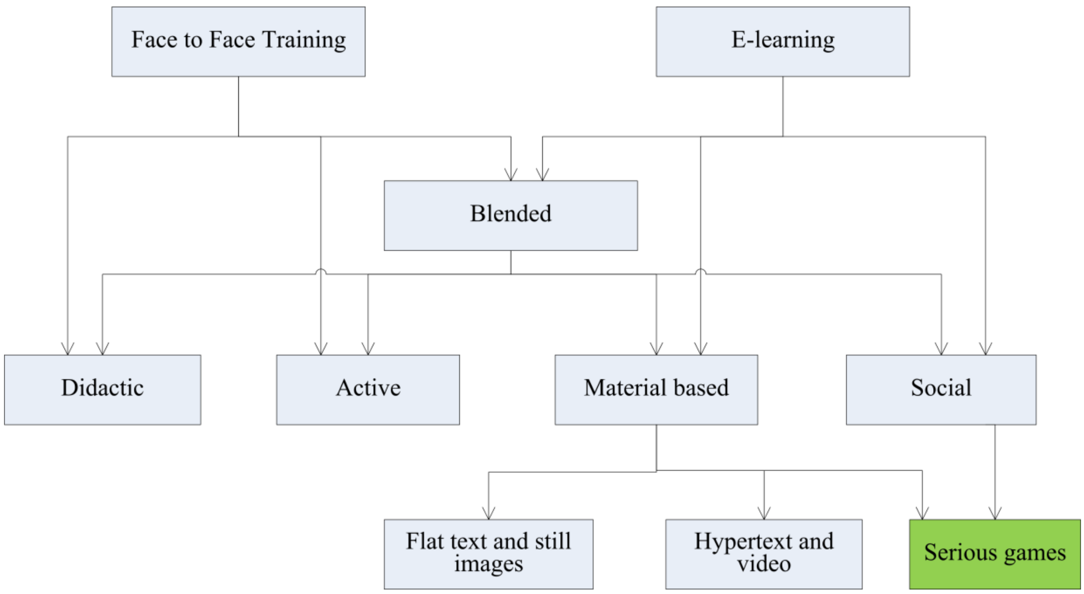


Fig. 1: Categorisation of Training in the Construction Industry

1.2 Challenges affecting the provision of training

There are many regulatory and commercial drivers in the EU that lead most companies to offer health and safety training to their employees (Felstead et al, 1999; Felstead et al, 2012). In the UK, the provision of training is supported by the ConstructionSkills levy scheme; an annual levy from employers is used to fund employers for training their workforce through programmes such as Construction Plant Competency Scheme (CPCS) and Site Safety Plus (Gambin et al, 2012). Despite this, the Health and Public Services Committee (2005) reported complacency about worker injury with less than a third of construction firms have training plans or a training budget. There were also concerns that, while the incidence of training may steady or even be increasing in the UK, the intensity and effectiveness of training may be falling, with training effort being spread more thinly among a higher proportion of workers (Felstead et al, 1999). Similarly, in the US, Van Buren & Erskine (2002) reported that, although the construction sectors has a high uptake of training (over 90% of employees receiving training), it was also one of the sectors with the lowest number of hours spent on training (15.3 hours per eligible employee) and with the highest ratio of employees to trainers (685:1). Goldenhar et al (2001) found that only 62% of employees questioned felt they had received Health and Safety training.

The fast pace of many building projects and tight deadlines can often impede effective safety training (Wall and Ahmed, 2008). One of the risk factors is the itinerant and casualised nature of employment in this sector (Health and Public Services Committee, 2005). The greater vulnerability of precarious workers has led to the development of the Pressures, Disorganization and Regulatory Failure (PDR) model, within which poor quality or absent training is seen as a serious risk factor (Underhill & Quinlan, 2011). Increased pressure on the training budget has also led to a tighter focus on specific business needs and increasing use of members of the regular workforce or a trade union representative to deliver training (Health and Public Services Committee, 2005; Felstead et al, 2011) and an increased interest in e-learning (Felstead et al, 2012).

1.3 The Quality of Training Provision

If training is to be fully effective it needs to have an impact on attitudes as well as behaviours. Somerville and Lloyd (2006) distinguished between how workers are trained to work safely and how they learn to work safely in workplaces, including building construction, and drew attention to the failure of safety training that was mediated through what they referred to as 'codified knowledge practices' associated with competency-based training. They considered that, in such training, the social and physical environments of the workplace are ignored and called for increased emphasis on these aspects of learning. The use of passive learning, often video scenarios and classroom type delivery at short 'toolbox talks' may be ineffective (Loosemore & Andonakis, 2007) and there has been concern that rapid initial training based on a didactic style may lead to confusion and misunderstanding (Guo et al, 2012). Cherrett et al (2009) identified the failure to capture the attention of learners sufficiently to impact on their ability to retain information and identification triggers for hazards. There may be additional difficulties if there are language barriers (Loosemore & Andonakis, 2007) and, as time is limited with many building projects, training is likely to be squeezed into the minimal amount of time possible (Felstead et al, 1999).

Hands-on and practical learning strategies allow a more active approach and are examples of Situated Learning, giving learners a chance to engage and make connections between the theoretical and the application. Participatory, peer led training was found to have a positive effect on attitudes, practices, and self-reported injury rates (Williams et al, 2010) but this usually takes place most effectively over an extended period of time, such as via an apprenticeship (Lave & Wenger, 2009).

The effectiveness of training can be linked to the quality of the provision, but it has long been known that the climate within a company, and the trainee's relationship with the company, can also have a positive or negative impact on training outcomes (Richey, 1990). Experience from related industries, such as mining, suggest that the interaction between how engaging the training experience is and the perceived hazardous nature of the industry can also have a significant impact on training outcomes (Burke et al, 2011) and, following a limited study, Edwards & Holt (2008) reported that perceived characteristics of training regimes used by employers did not appear to impact the outcomes of written tests of employees' health and safety knowledge.

2. E-LEARNING AS AN OPTION FOR SAFETY TRAINING

2.1 Information Transfer and e-Learning 1.0

Traditional uses of information technology (IT) and virtual learning environments (VLE's) have been materials based, as repositories for content (Nash, 2005; Minguillon et al, 2011). This provides easy and immediate access to content, but does not necessarily offer the benefit of contextualised and collaborative learning opportunities for participants (Acar et al, 2008; Addison & O'Hare, 2008). Materials are often accessed in support of a passive learning experience and content may include digitised versions of paper based information, video and pictorial content, lacking opportunities for dynamic interaction (Clark & Maher, 2001). Cherret et al (2009) suggest the shortcomings of basic streamed video can be significantly improved by endeavouring to make videos interactive through links to simulations and graphics amongst other learning materials. Arslan & Kivrak (2013) report the use of dramas and animations in Turkey to present construction accidents, claiming that visual materials can minimize accidents more effectively than purely theoretical training, especially for workers entering construction with a low level of education. Wall (2007) proposed the development of a virtual classroom framework with the specific focus on health and safety training for the construction industry. Using Gardner's (1983) work on multiple intelligences, which was originally intended to be applied to classroom based delivery, it was suggested that interactive material from webinars, hot spots in videos with images and photographs could be used to develop a learning activity.

The use of video, drama and hotspots allows learners to interact with the materials but they do not necessarily interact with their fellow learners or the trainer and, even with high quality materials, the e-learning 1.0 model is essentially isolating and individual. This makes it unattractive to students and possibly ineffective. It is unlikely that this approach can be seen an improvement on the toolbox talk, where there is at least the potential for communication with the trainer, although learning may be enhanced with a blended delivery approach, combining some face to face activity with support materials loaded to the VLE (Mackey, 2008).

2.2 Social E-Learning and e-Learning 2.0

Interaction and social collaboration in learning has often been identified as positive (Vygotsky, 1978; Deforges, 1995; Lombardi & McCahill, 2004; Wenger, 2008). E-learning 2.0 recognizes the importance of shared learning within a social context, rather than delivering static, passively learnt information (Dagada & Jakovljevic, 2004; Acar et al, 2008; Rajendran & Gambatese, 2009). While distance learning has been successfully transposed using IT where webinars and discussion groups have been a part of the learning design (Blanchard et al, 2006), Lombardi & McCahill (2004) are concerned that the current mechanisms available within VLE's do not provide the support offered by successful learner-centred communities based on constructivist pedagogy, suggesting that the sense of being within a learning space with other learners is lacking. Dagada & Jakovljevic (2004) identified the lack of social presence as a potential drawback for some learners who prefer to have the physical presence of tutors and other learners. Acar et al (2008) acknowledge the limitations of the experience for participants, recording participant satisfaction with the synchronous and asynchronous use of whiteboards and screen sharing as less favorable than face to face learning. Wang et al (2012) undertook a review of e-learning 2.0 studies and concluded that, while there is limited research comparing learning in conventional and e-Learning 2.0 environments, e-Learning 2.0 does appear to enable social learning and effective learning, with the potential to transfer learning to untrained tasks. However, there remains the question of how effective this approach will be for safety training on construction sites. Although it reintroduces the potential for social interaction, it is not necessarily practical in the way that "hands on" or "on site" learning might be. However, examining an array of safety learning and training methods (i.e. hands-on, lectures, films, video-based training, behavioral modeling and simulation) in terms of safety knowledge imparted, safety performance improved and safety outcomes, Burke et al. (2006) concluded that as the methods became more engaging and requiring trainees' active participation, workers demonstrated greater knowledge acquisition and reductions were seen in safety accidents and injuries.

3. VIRTUAL REALITY AND SERIOUS GAMES

The introduction of Virtual Worlds and Virtual Reality (VR) may hold the key to implementing a social element to e-learning strategies in the construction training. Serious Games and Games Based Learning (GBL) have become an area of interest to both educators and trainers over the last decade (Corti K, 2006). VR and GBL have the potential to provide not only the information required by learners, but the opportunity to build on that information together and so construct knowledge through that collaborative experience (van Nederveen, 2007).

Advances in technology and the use of simulators have learners to engage in simulated realities with rich visual and audio production and 3D environments, possibly displayed on wrap round screens, eliciting a semi-immersive response to the scenario (Westera et al, 2008; Ku & Mahabaleshwarkar, 2011; Goulding, 2012). In other fields, the immersiveness of this experience is sometimes further enhanced using a haptic interface to provide further sensory triggers for the participant, for example in rehabilitation (Rego, Moreira, & Reis, 2010) surgery (Våpenstad et al., 2013) or in flight simulators. The use of GBL may allow a type of Situated Learning, providing a similar opportunity for learners to engage and make connections between theory and application (Squire, 2006) and evidence is growing that the immersive and repeatable aspects of serious games allow participants to learn through doing in an Experiential Learning style (Coyne, 2003; Van Eck, 2006; Susi et al, 2008; Goulding, 2012). Westera et al (2008) suggest that GBL can be used to provide participants with the necessary detail to allow them to learn complex skills through focused scenario-based games. Lin et al (2011) suggest that static pictures of hazards limit learners discussions to what is in the image, whereas walking a 3D simulation provides them with the opportunity to link different factors identified in the walk through, potentially promoting deep learning rather than surface learning. Combining Web 2.0 technologies with VR has proved popular with students (Wang et al, 2012). Simulations have been found to help contextualise learning for participants in the construction industry (Wall & Ahmed, 2008).

There are simulations and virtual worlds available that run on simple desktop computers and open source options provide an inexpensive option to experiment with the development of serious games to suit industry requirements. For example, the use of virtual worlds such as Second Life may provide options for low cost developments that emulate real world activities (Boulos et al, 2007). Virtual environments such as this have the advantage of allowing creators to access other user created content, thus speeding up the build phase of activity development (Kaplan & Haenlein, 2010). Two examples of rapidly construction site scenarios developed relatively rapidly in Second Life are shown in Figure 2. In addition the collaborative opportunities for learners within the virtual environment may offer a distinct advantage over the rigid and individual human to computer interface often experienced with serious games designs (Antonacci & Modress, 2008). Ku & Mahabaleshwarkar (2011) used Second Life to deliver construction safety to students. Students were asked to collaborate to create content (buildings) whilst considering safe working practices. The limitations of this approach were mostly related to the challenges making the environment 'real' due to relatively unsophisticated graphics and limited representations real world physics, but the authors found that the learning experience was still effective.

Lin et al. (2011) have considered how closely the game or environment has to emulate reality in order to create the desired immersive sensations and reactions, suggesting that high realism may not be cost effective in terms of developing effective educational games for some applications. To emulate reality and in particular the evolving construction site over time, Miller et al. (2012) have proposed to embed the concept of 4D planning (i.e. 3D virtual content changing over time) within the virtual world. Lin et al. (2011) suggested that reality can be emulated in a cost effective way by using traditional images and video footage within the game, but recognised that this may break the sense of presence and interrupt the learning activity. This limitation might be addressed through the use of an integrated Head-up Display (HUD) system within the virtual world platform of Second Life. For example, the developer of the Prohawk HUD has designed it to deliver an uninterrupted learning experience using scripted objects that provide feedback and guidance to learners. This allows participants to make choices, for example about the correct tools for excavation of particular layers of earth, and to learn from their choices (Romulus, 2011). Information about performance of participants throughout the task can also be gathered by the HUD system and reported back to trainers.

Fig. 2: Site safety explored in a virtual build

3.1 Virtual Prototyping

As well as generic safety skills and knowledge, construction workers, the safe design of sites is also important (Hide at al., 2003). Virtual Prototyping and 4D solutions are already employed in the design of safe sites and in the education of civil engineers and architects. Virtual Prototyping (VP) uses modeling and simulation to aid in the identification of unsafe factors in site design and can also be used to provide safety training. Goedert et al (2011) suggest that the use of simulations in the education of students intending to enter the construction industry can produce graduates who are competent for that entry to the workplace. The use of 3D and 4D (3D +time) modeling to aid architectural and engineering student development was found to be extremely valuable (Lee et al, 2011). The ability for students to be able take a 2 dimensional design and reconstruct it within a virtual environment that supports 3D or 4D modeling allows the student designers to investigate their build design from the perspective of an end user. Guo et al (2013) have presented a case study demonstrating the use of VP to improve the safety performance of construction projects.

Shen at al (2012) used building information modelling (BIM) to develop a 3D learning activity aimed at educating hospital facility management, concluding that virtual environments offered the opportunity to provide learning and training where the context of a particular built environment was important to the learning. Workers need to be able to recognise specific hazards associated with particular construction sites, especially complex sites and there have been calls for better methods to develop hazard recognition skills among new workers (Albert & Hallowell, 2012). Applying this approach within a construction scenario may provide participants may address some of the issues previously discussed by Dagada & Jakovljevic (2004) and Acar et al (2008).

4. CONCLUSION

Traditional face to face delivery of health and safety training in the construction industry, for example via toolbox talks, does not seem to be changing attitudes and so is not making a significant impact on the numbers of accidents (Choudhry & Fang, 2008). As further pressure is placed on training budgets, through time constraints and the increased training needs of a vulnerable workforce, there may be a significant deterrent to providing high quality training, including hands on practical training. The introduction of e-learning 1.0 may be a step backwards if a flat materials based approach is adopted, and while the advantages of social learning styles are acknowledged, it is considered unlikely that discussion forums and some other approaches used in the e-Learning 2.0 will be effective at this level. On the other hand, the introduction of a GBL model using simple VR to address the needs of both learners and employers may provide a flexible, adaptable and cost effective solution. The increased use of the VP outputs in safety training for site staff may also be beneficial in providing context specific training.

5. REFERENCES

Acar, E., Wall, J., McNamee, F., Carney, M., & Öney-Yazici, E. (2008). Innovative safety management training through e-learning. *Architectural Engineering and Design Management*, *4*(3-4), 239-250.

Addison A & O'Hare, WT. (2008). How Can Massive Multi-user Virtual Environments and Virtual Role Play Enhance Traditional Teaching Practice? ReLive 08 Researching Learning in Virtual Environments (pp. 7 - 16). Milton Keynes: The Open University.

Albert, A. & Hallowell, M. R. (2012) Hazard Recognition Methods in the Construction Industry. Construction Research Congress 2012 © ASCE 2012, 407-416.

Anderson, M. (2005). Behavioural Safety and Major Accident Hazards: Magic Bullet or Shot in the Dark?. *Process Safety and Environmental Protection*,*83*(2), 109-116.

Antonacci, D. M., & Modaress, N. (2008). Envisioning the educational possibilities of user-created virtual worlds. *AACE Journal*, *16*(2), 115-126.

Arslan G & Kivrak S. (2013). Health and safety trainings in construction using dramas and animations. Retrieved June 30, 2013 from http://bildiri.anadolu.edu.tr/papers/bildirimakale/5653_b628k50.pdf.

Burke, M.J. et al. (2006). Relative effectiveness of worker safety and health training methods. *American Journal of Public Health*, Vol. 96 (2), 315-324.

Blanchard, R.E., Moron-Garcia, S.D., & Bates, M.R., “Converting the physical to the virtual: providing a laboratory experience for distance learners in engineering”, Current Developments in Technology-Assisted Education, 2006, pp. 1208-1213.

Bonwell, C. C., & Eison, J. A. (1991). Active learning: Creating excitement in the classroom (*ASHE-ERIC Higher Education Report N. 1*). Washington, DC: The GeorgeWashington University, School of Education and Human Development.

Boulos, M. N. K., Hetherington, L., & Wheeler, S. (2007). Second Life: an overview of the potential of 3-D virtual worlds in medical and health education. *Health Information & Libraries Journal*, *24*(4), 233-245.

Bureau of Labor Statistics. National census of fatal occupational injuries in 2011. Washington, DC: US Department of Labor, Bureau of Labor Statistics, Safety and Health Statistics Program; 2010. Retrieved June 30, 2013, from Bureau of Labor Statistics: http://www.bls.gov/news.release/archives/cfoi_08252011.pdf

Burke, M. J., Salvador, R. O., Smith-Crowe, K., Chan-Serafin, S., Smith, A., & Sonesh, S. (2011). The dread factor: how hazards and safety training influence learning and performance. *Journal of Applied Psychology*, *96*(1), 46.

Bust, P. D., Gibb, A. G., & Pink, S. (2008). Managing construction health and safety: Migrant workers and communicating safety messages. *Safety Science*,*46*(4), 585-602.

Cherrett, T., Wills, G., Price, J., Maynard, S., & Dror, I. E. (2009). Making training more cognitively effective: Making videos interactive. *British Journal of Educational Technology*, *40*(6), 1124-1134.

Choudhry, R. M., & Fang, D. (2008). Why operatives engage in unsafe work behavior: Investigating factors on construction sites. *Safety science*, *46*(4), 566-584.

Clark S. & Maher, M.L. (2001). The Role of Place in Designing a Learner Centred Virtual Learning Environment. In S. C. Maher, & J. v. Bauke de Vries (Ed.), Computer Aided Architectural Design (CAAD) Futures 2001 (pp. 187-200). Eindhoven, The Netherlands: Springer .

Corti K. (2006). Games-based Learning; a serious business application. Informe de PixelLearning, 34(6), 1 - 20.

Coyne, R. (2003). Mindless repetition: Learning from computer games. *Design Studies*, *24*(3), 199-212.

Dagada, R., & Jakovljevic, M. (2004, October). 'Where have all the trainers gone?'E-learning strategies and tools in the corporate training environment. In*Proceedings of the 2004 annual research conference of the South African institute of computer scientists and information technologists on IT research in developing countries* (pp. 194-203). South African Institute for Computer Scientists and Information Technologists.

Deforges, C. (1995). How does experience affect theoretical knowledge for teaching. Learning and Instruction 5(4), 385-400.

Edwards D J & Holt G D. (2008). Construction workers' health and safety knowledge: Initial observations on some test-result data. Journal of Engineering, Design and Technology, 6(1), 65-80.

Fang, D., & Wu, H. (2013). Development of a Safety Culture Interaction (SCI) model for construction projects. *Safety Science*, *57*, 138-149.

Felstead, A., Green, F., & Mayhew, K. (1999). Britain's training statistics: a cautionary tale. *Work, Employment and Society*, *13*(01), 107-115.

Felstead, A., Green, F., & Jewson, N. (2012). An analysis of the impact of the 2008–9 recession on the provision of training in the UK. *Work, Employment & Society*, *26*(6), 968-986.

Fuller A & Unwin L. (2003). Fostering Workplace Learning: looking through the lens of apprenticeship. European Educational Research Journal, 2(1), 1-15.

Gambin, L., Hogarth, T., Atfield, G., Li, Y., Owen, D., Breuer, Z., & Garrett, R. (2012). Sector skills insights: construction. London: UK Commission for Employment and Skills UKCES.

Garavan, T. N. (1997). Training, development, education and learning: different or the same?. *Journal of European Industrial Training* 21 (2), 39-50

Gardner, H. (1983). Frames of Mind — The Theory of Multiple Intelligences. New York: Basics.

Goedert, J., Cho, Y., Subramaniam, M., Guo, H., & Xiao, L. (2011). A framework for virtual interactive construction education (vice). *Automation in Construction*, *20*(1), 76-87.

Goldenhar, L. M., Moran, S. K., & Colligan, M. (2001). Health and safety training in a sample of open-shop construction companies. *Journal of safety Research*, *32*(2), 237-252.

Goulding, J., Nadim, W., Petridis, P., & Alshawi, M. (2012). Construction industry offsite production: A virtual reality interactive training environment prototype. Advanced Engineering Informatics, 26(1), 103-116.

Guo, H., Li, H., Chan, G., & Skitmore, M. (2012). Using game technologies to improve the safety of construction plant operations. *Accident Analysis & Prevention*, *48*, 204-213.

Guo, H. L., Li, H., & Li, V. (2012). VP-based safety management in large-scale construction projects: A conceptual framework. Automation in Construction, 34, 16-24.

Health and Public Services Committee. (2005). Building London, saving lives Improving health and safety in construction. London: Greater London Authority.

Hide, S., Atkinson, S., Pavitt, T. C., Haslam, R., Gibb, A. G., & Gyi, D. E. (2003). *Causal factors in construction accidents*. © Health and Safety Executive.

Ho, C. L., & Dzeng, R. J. (2010). Construction safety training via e-Learning: Learning effectiveness and user satisfaction. *Computers & Education*, *55*(2), 858-867.

Health and Safety Executive (2011) Construction: Work related injuries and ill health. HSE. [Online]. Available fromhttp://www.hse.gov.uk/statistics/industry/construction/construction.pdf

Jensen, J. (2001). Improving training in order to upgrade skills in the tourism industry. Tourism and Employment, Final Report of Working Group B, European Commission.

Kaplan, A. M., & Haenlein, M. (2010). Users of the world, unite! The challenges and opportunities of Social Media. *Business horizons*, *53*(1), 59-68.

Ku, K., & Mahabaleshwarkar, P. S. (2011). Building interactive modeling for construction education in virtual worlds. *Journal of Information Technology in Construction*, *16*, 189-208.

Lapinski, M. K., & Rimal, R. N. (2005). An explication of social norms. Communication Theory, 15(2), 127-147.

Lave, J., & Wenger, E. (2009). Situated Learning - Legitimate peripheral participation. (R. Pea, Ed.) Cambridge: Cambridge University Press.

Lee, S., Nikolic, D., Messner, J. I., & Anumba, C. J. (2011). The Development of the Virtual Construction Simulator 3: An Interactive Simulation Environment for Construction Management Education. In *Computing in Civil Engineering (2011)* (pp. 454-461). ASCE Publications.

Leslie R. (1995). *Techniques of Training (3rd Ed)*, Aldershot: Gower publishing limited

Lin, K. Y., Son, J. W., & Rojas, E. M. (2011). A pilot study of a 3D game environment for construction safety education. *Journal of Information Technology in Construction*, *16*, 69-83.

Lombardi, J., & McCahill, M. P. (2004, January). Enabling social dimensions of learning through a persistent, unified, massively multi-user, and self-organizing virtual environment. In *Creating, Connecting and Collaborating through Computing, 2004. Proceedings. Second International Conference on* (pp. 166-172). IEEE.

Lombardi, D. A., Pannala, R., Sorock, G. S., Wellman, H., Courtney, T. K., Verma, S., & Smith, G. S. (2005). Welding related occupational eye injuries: a narrative analysis. *Injury Prevention*, *11*(3), 174-179.

Loosemore, M., & Andonakis, N. (2007). Barriers to implementing OHS reforms–The experiences of small subcontractors in the Australian Construction Industry. *International Journal of Project Management*, *25*(6), 579-588.

Mackey, J. (2008). Blending real work experiences and virtual professional develpoment. Proceedings ascilite Melbourne 2008.

Miller, G., Dawood, N., and Kassem, M. (2012). Building an Emergent Learning Environment for Construction Health and Safety by Merging Serious Games and 4D Planning. In: *Proceedings of the 2012 ASCE International Conference on Computing in Civil Engineering*, pp.129-136

Minguillón, J., Sicilia, M. A., & Lamb, B. (2011). From Content Management to E-Learning Content Repositories. In *Content Management for E-Learning* (pp. 27-41). Springer New York.

Nadler, L. (1984). *The Handbook of Human Resource Development*. New York: John Wiley & Sons.

Nash, S. S. (2005). Learning Objects, Learning Object Repositories, and Learning Theory: Preliminary Best Practices for Online Courses. Interdisciplinary Journal of Knowledge and Learning Objects, 1, 217-228.

Parker, A. (2006). Lifelong learning to labour: apprenticeship, masculinity and communities of practice. *British Educational Research Journal*, *32*(5), 687-701.

Premji S & Smith P M. (2012). Education-to-job mismatch and the risk of work injury. Injury Prevention. Injury Prevention, 19(2), 106 - 111.

Rajendran, S., & Gambatese, J. A. (2009). Development and initial validation of sustainable construction safety and health rating system. *Journal of Construction Engineering and Management*, *135*(10), 1067-1075.

Redecker, C., Ala-Mutka, K., Bacigalupo, M., Ferrari, A., & Punie, Y. (2009). Learning 2.0: The impact of Web 2.0 innovations on education and training in Europe. *Final Report. European Commission-Joint Research Center-Institute for Porspective Technological Studies, Seville*.

Rego, P., Moreira, P. M., & Reis, L. P. (2010). Serious games for rehabilitation: A survey and a classification towards a taxonomy. In 5th Iberian Conference on Information Systems and Technologies (CISTI) (pp. 1-6). IEEE.

Richey, R.C. (1990) The Effects of Organizational Climate Factors on Industrial Training Outcomes, paper presented at the Convention of the Association for Educational Communications and Technology, February, Iowa, Iowa.

Romulus, P. (2011). Prohawk HUD. Retrieved 2013, from Second Life - Prometheus Romulus: https://my.secondlife.com/en/prometheus.romulus

Sarason, Y. and Banbury, C. (2004).Active Learning Facilitated by Using a Game-Show Format or Who Doesn't Want to be a Millionaire?, Journal of Management Education, 2004, 28: 509. .

Sawacha, E., Naoum, S., & Fong, D. (1999). Factors affecting safety performance on construction sites. *International Journal of Project Management*, *17*(5), 309-315.

Shen, Z., Jiang, L., Grosskopf, K., & Berryman, C. (2012). Creating 3D web-based game environment using BIM models for virtual on-site visiting of building HVAC systems. In *Construction Research Congress 2012@ sConstruction Challenges in a Flat World* (pp. 1212-1221). ASCE.

Somerville M & Lloyd A. (2006). Codified knowledge and embodied learning: the problem of safety training. Studies in Continuing Education, 28(3), 279-289.

Squire, K. (2006). From content to context: Videogames as designed experience. *Educational researcher*, *35*(8), 19-29.

Susi, T., Johannesson, M., & Backlund, P. (2007). Serious games: An overview. University of Skövde, School of Humanities and Informatics, Institutionen för kommunikation och information. Stockholm: School of Humanities and Informatics University of Skövde, Sweden.

Swuste, P., Frijters, A., & Guldenmund, F. (2012). Is it possible to influence safety in the building sector?: A literature review extending from 1980 until the present. *Safety Science*, *50*(5), 1333-1343.

Toole, T. M. (2002). Construction site safety roles. *Journal of Construction Engineering and Management*, *128*(3), 203-210.

Underhill, E., & Quinlan, M. (2011). How precarious employment affects health and safety at work: the case of temporary agency workers. Relations industrielles/Industrial Relations, 66(3), 397-421.

Van Buren, M. E., & Erskine, W. (2002). The 2002 ASTD state of the industry report. Alexandria, VA: ASTD.

Van Eck, R. (2006). Digital game-based learning: It's not just the digital natives who are restless. EDUCAUSE Review, 41(2), 16 - 30.

van Nederveen, S. (2007). COLLABORATIVE DESIGN IN SECOND LIFE. In H. A. Wamelink (Ed.), Second International Conference World of Construction Project Management 2007. Delft: TU Delft.

Våpenstad, C., Hofstad, E. F., Langø, T., Mårvik, R., & Chmarra, M. K. (2013). Perceiving haptic feedback in virtual reality simulators. Surgical endoscopy, 1-7.

Veldhuis-Diermanse A.E. (2002). CSCLearning? Participation, learning activities and knowledge construction in computer-supported collaborative learning in higher education. *Ph.D. Dissertation*, Wageningen University, Wageningen.

Vygotsky, L. S. (1978). Mind in Society: The Development of Higher Mental Processes. Cambridge: Harvard University Press.

Wall, J., & Ahmed, V. (2008). Use of a simulation game in delivering blended lifelong learning in the construction industry–Opportunities and Challenges. *Computers & Education*, *50*(4), 1383-1393.

Wall, J., Carney, M., McNamee, F., Madden, D., Hurst, A., Vrasidas, C., & Jordan, A. (2007, September). The delivery of health and safety training applying multiple intelligences using virtual classes. In *23rd Annual ARCOM Conference* (pp. 3-5).

Wang, X., & Klinc, R. (2012). EDITORIAL: Special issue on eLearning 2.0: Web 2.0-based social learning in built environment.. Journal of Information Technology in Construction, 17, 386-387.

Wenger, E. (2008). Communities of Practice Learning, Meaning and Identity. (R. Pea, Ed.) Cambridge: Cambridge University Press.

Westera, W., Nadolski, R. J., Hummel, H. G., & Wopereis, I. G. (2008). Serious games for higher education: a framework for reducing design complexity. *Journal of Computer Assisted Learning*, *24*(5), 420-432.

Williams Jr, Q., Ochsner, M., Marshall, E., Kimmel, L., & Martino, C. (2010). The impact of a peer-led participatory health and safety training program for Latino day laborers in construction. *Journal of Safety Research*, *41*(3), 253-261.

Young H P. (2007, January). Social Norms. Oxford, Oxfordshire, England: University of Oxford; Department of Economics. Retrieved June 23, 2013, from http://economics.ouls.ox.ac.uk/13475/1/Item.pdf

A DISTRIBUTED VIRTUAL REALITY APPLICATION FRAMEWORK FOR COLLABORATIVE CONSTRUCTION PLANNING USING BIMSERVER[1]

Wei Zhou & Joseph Tah
Department of Real Estate and Construction, Faculty of Design, Technology & Environment, Oxford Brookes University, Headington Campus, Oxford, OX3 0BP, UK

David Heesom
School of Technology, University of Wolverhampton, Wulfruna Street, Wolverhampton, WV1 1LY, United Kingdom

ABSTRACT: *As the architecture/engineering/construction (AEC) industry proceeds in the direction of digitalisation, computer supported collaborative work (CSCW) enhanced by building information modelling (BIM) becomes realistic for multidisciplinary collaboration in construction. Networked virtual reality (VR) supported by BIM servers, though showing great potentials in connecting multidisciplinary teamwork, is still less clarified for geographically dispersed construction teams to achieve collaboration. Taking the advantages of networked VR through the BIM server connection, this paper discusses a BIMserver-based VR application framework for distributed teams to perform real-time collaborative 4D construction planning and simulation. Through the analysis of current 4D modelling approaches, BIMserver adoption for collaborative 4D planning, as well as enabled VR platform technologies, the paper highlights availabilities of the interactive definition method for collaborative 4D planning underpinned by BIMserver. This method supports CSCW activities like co-navigate, so-sort, co-plan, co-simulate and co-talk for the 4D planning teamwork, together with power wall based semi-immersive VR platform for accommodating group users. On the basis of these discussions, a BIM-VR groupware system named Co-Studio is depicted from system architecture and application features. These discussions lay a foundation to develop a full functioned Co-Studio system as a next step. The system's applicability will be verified and validated in its subsequent implementation and industry projects.*

KEYWORDS: *BIMserver, collaborative 4D planning, groupware, virtual reality*

1. INTRODUCTION

A construction plan plays a fundamental role in construction management. A rigorous construction plan is the basis for developing the budget and the schedule for work. Depending on this function, the construction plan can further help formulate correct strategies for coordinating different construction activities. Thus the on-site conditions are foreseeable in the light of the conceived construction panorama. In view of its complicated nature, creating a construction plan, especially a robust plan, is a critical task in construction management. A useful approach in forming a construction plan is to simulate the construction process either in the imagination of the planner or with a formal computer based simulation technique (Hendrickson, 1989). However, the planner's imagination for construction planning is dependent on individual's experience and knowledge. A concern over skill shortages in this field is increased because junior staff usually has insufficient on-site experience to play this role like retired planners (Winch, 2002). With the advancement of information communication technologies (ICT), the computer based simulation is the more dependable approach to a robust plan.

4D (3D plus time) CAD is the one of computer based methods to generate construction simulations (Collier and Fischer, 1996). By linking a construction schedule with a 3D model, 4D can generate a dynamic construction sequence. This kind of simulation allows the user to preview a construction process so that potential conflicts in the schedule can be disclosed before the project delivery. The research interests of this technology have become

[1] Citation: Zhou, W., Heesom, D. & Tah, J. (2013). A distributed Virtual Reality application framework for collaborative construction planning using BIMserver. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

increasingly active due to its great potentials. In order to explore more benefits for the Architecture / Engineering / Construction (AEC) industry, substantial efforts have been invested into different facets of 4D CAD in product and process modelling (Heesom and Mahdjoubi, 2004). Being further extended, the use of 3D building model had been considered to connect multiple dimensions to investigate more AEC issues like health-safety, energy, cost, etc. An example is the nD modelling project conducted by the University of Salford in the United Kingdom. This kind of 3D based building information modelling (BIM) technology has led to the more extensive discussion for effective application in the AEC field (Succar, 2009).

Although having reached the stage of advanced BIM application, the construction industry still faces up a challenge in applying 4D CAD technologies for distributed collaboration. One of the weaknesses of 4D CAD lies in its insufficient support for geographically dispersed subcontractors. In the industry, the Critical Path Method (CPM) is popular in making a construction plan (InJongbeling et al, 2006). The CPM-based 4D CAD creation mainly relies on experienced engineers' imagination in accordance with blueprints (Chau et al, 2005). Moreover, subcontractors in a project specialise in their own fields, and concentrate on their own project planning in different locations. It is apparent that their static, abstract, and isolated schedules are incapable to deal with dynamic on-site situations. Although 4D technologies are helpful to disclose hidden contradictions in a project plan, prevailing stand-alone 4D tools have modest capabilities to support true distributed collaboration. Targeting this limitation, virtual reality (VR) based 4D groupware was envisaged as a viable approach to involving subcontractors into a unified 3D virtual environment for collaborative planning (Zhou et al, 2006). In spite of being successfully deployed in diverse fields, VR technologies are unbalanced in utilisation in the AEC industry. Most VR applications focus on the design phase but not the more complex and dynamic construction phase.

It was reported that (semi-) immersive VR systems are used for constructing interactive workspaces, such as CIFE iRoom at Stanford University, Interactive Collaboration Laboratory (ICL) at the University of New Brunswick in Canada, the Immersive Environment Laboratory (IEL) at Pennsylvania State University, etc. Recent reports (Issa, 2007; Muramoto, 2007) show that (semi-) immersive VR systems as a part of infrastructure are closely combined with the high bandwidth network to build a tele-collaborative environment. This inception intends to enhance information communication for rich modes of creative activity and collaboration. Compounded with these VR systems, extra equipments include interactive tabletop display, audio/video conferencing systems, and interactive board with touch-screen capability, special digital pen and eraser, etc. Users can interact with these devices using wireless mouse or even their fingers. These sorts of interactive workspaces are dedicated to creating a tele-collaborative educational environment in the AEC sector for general design and education purposes. The success from these reports prompts that a tele-collaborative VR environment can be a feasible platform for collaborative 4D construction planning in the condition of running suitable 4D groupware for a group of geographically dispersed planners.

The use of BIM models in the server end can enhance the network infrastructure of a tele-collaborative VR environment, and hence positively improve the productivity of collaborative 4D planning performed in it. Applying BIM models, particularly the industry foundation classes (IFC), for 4D planning is verified to be an effective way to integrate both 3D building entity information and plan data into a unique database (Tanyer and Aouad, 2005). However, the reported successful case was about individual planning using IFC data files rather than networked collaborative work applying IFC model servers. The latter is recommended for wide adoption to reduce disparity for data presentation and decrease incompatibility in data exchange among clients (Kam et al, 2003). Given an IFC-compliant BIM server, geographically dispersed planners are able to share the same project information and more effectively and efficiently manage their work. This possibility becomes realistic with the advent of open source building information model server – the BIMserver (BIMserver, 2013). Since it applies IFC for creating a building project information repository, the server can thus synthesise all project-related information provided from the client ends, update related IFC objects in the database, and then dispatch it to every client in real time. It can minimise BIM interoperability problems among different clients accessing the same IFC database to achieve integrated project delivery.

The objective of this paper is to discuss a 4D-VR groupware application framework applying the open source BIM model server – BIMserver for distributed collaborative construction planning. Through the review of the state-of-the-art of construction simulation technology, it highlights the viability of the interactive definition method for collaborative 4D planning by applying the BIM model server. From technological and constructional perspectives, it further discusses IFC-compliant BIM model server and enabled VR platform technologies respectively. Based on these discussions, a power wall based semi-immersive IFC-compliant 4D/VR groupware framework named Co-Studio is proposed from a constructional perspective.

2. CONSTUCTION PLANNING AND COLLABORATIVE 4D MODELLING

Using computer to simulate a construction process is helpful to generate a robust construction plan. According to the level of detail in the project control, related simulation approaches are classified to be product modeling and operation modeling. Product modeling at a project level can be applied for visually examining a developed construction plan; and operation modeling at an operational level can create a construction plan after the simulation (Kamat, 2003). Taking geographically dispersed condition into account, a construction plan can be also achieved through a collaborative 4D approach (Zhou et al, 2009). This section discusses and analyses existing investigations in these areas.

2.1 Modeling based construction planning

Current modeling based construction planning can be performed via both macro and micro approaches. From a macro perspective, the product modeling, which can be further developed into process modeling, follows the top-down approach to visualizing a created project plan (Figure 1). Its basic mechanism is to decompose a 3D model and link its elements (Product Breakdown Structure, PBS) with specific schedule activities (Work Breakdown Structure, WBS) to be a visualized construction sequence. Along with time progress, 3D elements appear in their last spatial locations, thus their corresponding schedule activities can be visually examined for contradiction identification. This dynamic product presentation provides planners with visual insights for controlling construction at the project level (Koo and Fisher, 2001). Compared with traditional Gantt chart based schedule, using final product to disclose potential logical, spatial and temporal problems in the schedule can lead to a relevantly robust construction plan.

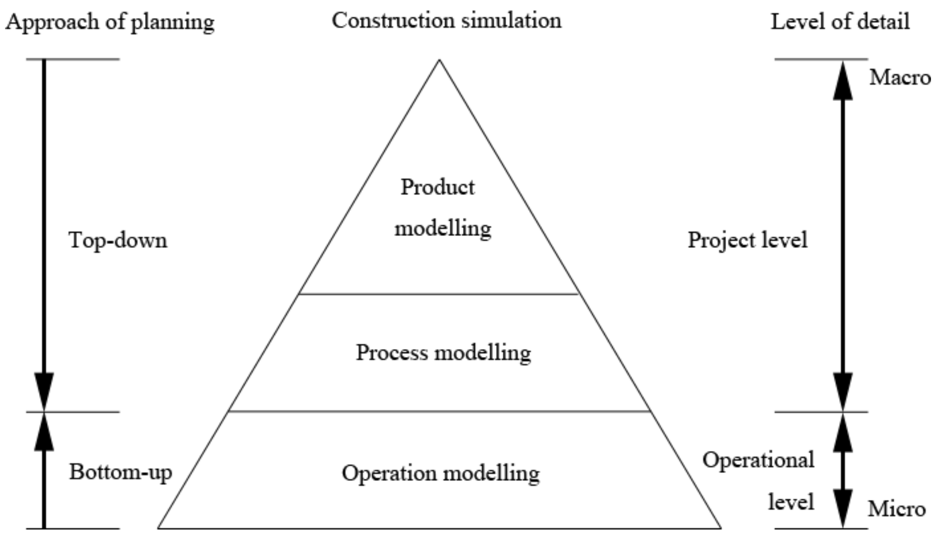


Fig. 1: Modelling based construction planning

The CPM-based 4D CAD is a typical top-down product modelling. In its creation, the project schedule needs to be generated using bar chart in advance. Afterwards, it can be visually checked and enhanced by linking the 3D elements (Collier and Fischer 1996). Normally, the linking → checking → updating procedure needs to be repeated several times to incrementally guarantee a conflict-free plan. For assisting conflict identification, relevant research concentrates on its visualisation, e.g. CIFE 4D Annotator (McKinney-Liston, 1998). The top-down approach is also applied in process modelling. On the basis of product modelling, process modelling emphasises analytical information such as cost, space usage, site layout etc. (Heesom and Mahdjoubi, 2004). Different methods are demonstrated for seeking more reliable plans in these areas, e.g. multi-constraint planning (Sriperate and Dawood, 2003), critical space analysis (CSA) (Dawood, 2004), location-based (or line-of-balance, LOB) 4D simulation (InJongbeling, 2006), etc. Because of separate 3D model and schedule creation, more feasible ways are needed in the top-down approach to automating the connection of 3D model with the schedule.

From a micro perspective, operation modelling can generate a project plan following the bottom-up approach. In contrast to product and process modelling, operation modelling deals with the dynamic motion of resources and facilities used during operations. It can visualise not only project level activities, but also motion of resources used by construction activities (Tantisevi, 2007). As 4D CAD only depicts the evolution of the construction product rather than the interaction of its consumed resources, operation modelling focusing on work at the field or operational level can naturally achieve the evolving product as its by-product (Kamat, 2003). Accordingly, its construction plan can be derived from this by-product. Li (2003) indicated this approach applying a knowledge-based VR system, the Virtual Construction Laboratory (VCL). The VCL can support construction planners to simulate construction activities in order to evaluate construction operations. In its operational level simulation, the planner's activities performed in the VCL can be recorded, and become the base for automating construction schedule generation. In such an approach, the system produces construction schedule according to the planner's activities.

In general, the top-down approach in product and process modelling is the prevailing way to obtain a robust construction plan. The application of 4D technologies mainly adopts this approach in the industry. The bottom-up approach, on the other hand, is mainly discussed in the research field. Compared the top-down approach with the bottom-up approach, the former is straightforward and explicit whilst the latter is indirect and implicit. Besides these differences, the top-down approach features iteration and inflexibility in modelling creation while the bottom-up approach bears accuracy with extra workload for the resources and facilities simulation.

2.2 Collaborative 4D planning

Collaborative 4D planning enables planners to create and integrate WBS based on their shared PBS in a geographically dispersed condition. It is different from stand-alone 4D modelling, which require individual's work on a created 3D building model without sharing PBS-WBS information with collaborators. Since the 4D CAD initiation nearly two decades ago, reported 4D creation methods and construction planning ways mainly concentrate on stand-alone applications for product modelling. Targeting this pitfall, the interactive definition method follows a top-down modelling approach to distributed collaborative 4D planning (Zhou et al, 2009). It emphasises an inputted 3D model to be accessible across the Internet. The PBS of the 3D model can be obtained by geographically dispersed planners via the network, and hence they are able to create WBS in their local places concurrently. Its related 4D simulation is also developed along with the WBS creation. The outcome of this collaborative planning has an integrated WBS - the construction plan, and completed 4D simulation.

The interactive definition method specifies a distributed real-time collaborative working context, in which a collaborative community and collaborators' behaviours are defined by CSCW dimensions, such as time, space, group size, interaction style, etc.(Mills, 2003). Applying this method, 4D collaborative planning work can be achieved by a geographically dispersed planning team. Every team member specialises in different fields such as structure, HVAC, electricity, etc to perform their own work individually and collaboratively. In the offline condition, planners can perform their individual work like other stand-alone 4D applications. In the online condition for collaboration, they can interact with each other for concurrent planning using their local devices like wired or cordless PC, mobile, etc. The planners can fully control their own information and obtain other planners' information synchronously. Basically, they can perform five types of work in their collaboration including co-navigate, co-sort, co-plan, co-simulate, and co-talk.

A prototype named 4DX implemented full features of the interactive definition method (Zhou et al, 2012) based on the desktop platform. In its collaborative functions, co-navigate and co-sort were created for analysing spatial structure of 3D building model. As every defined plan task in 4D planning is based on specific 3D model entities, these co-navigate and co-sort operations allowed planners to manually filter out their domain-related entities for plan data creation. Co-plan and co-simulate played a dominant role in the group planning. Co-plan was designed to support planners to access PBS from different locations, distribute local planners' schedule information, as well as receive other schedule information from remote planners. During the co-plan process, co-simulate across the network was positive for multiple planners to co-discover potential conflicts from a co-created plan (Kang et al. 2007). Multidisciplinary planners hence could focus on not only their own but also integrated whole plan's simulation. Co-talk could make use of audio and videoconferencing to achieve human-human interaction to facilitate collaboration during the planning.

3. BIMSERVER AND VR TECHNOLOGIES

The interactive definition method indicates a possibility of adopting advanced BIM model server and VR technologies into distributed real-time collaborative 4D planning groupware. It will be positive to connect geographically dispersed planners across time and place for communication, collaboration and integration. This section discusses the adoption of BIMserver and enabled VR technologies for the 4D groupware investigation.

3.1 BIMserver adoption

BIMserver is an open source project dedicated to the AEC industry to apply IFC as model server (BIMserver, 2013). It allows users to easily customise the server environment to suit their own needs, such as reuse, modify and adapt implementations of low-level tasks like underlying EXPRESS schema and instance parsing, persistency management and visualization. Besides the low-level operations, it provides developers with service interfaces of SOAP (Simple Object Access Protocol), JSON (JavaScript Object Notation), etc. to communicate with the server though a large collection of created methods. Developers thus can create their own client applications to fully take the advantage of BIMserver using any programming languages.

The freely accessible BIMserver provides excellent opportunities to create sophisticated 4D planning groupware. One of benefits is to enhance server management. The reported 4DX planning groupware took a server-client mode to create related functionalities. It applied entity-based 3D building models and separate plan data storage in the server end so that planners in the client ends can download the whole model and data, and then identify their domain-related entities for 4D planning. The building entities and plan data were loosely managed in the server since they were not synthesised into building models. However, BIMserver can significantly improve the server functions to integrate both entity and plan information in the database. Because IFC models contain both graphical and semantic information, which can be presented by product models like building entities and non-product models like cost, plan, energy, etc.(Froese, 2003), BIMserver therefore can simplify the server management by using IFC models only to restore both graphical and semantic information into a central project repository.

Applying BIMserver in the 4D planning groupware will also provide convenience for planners to perform their individual and collaborative work. In the entity-based 4D planning groupware, planners need manually pick out their domain-related entities for plan task definition. It costs amount of time to prepare a 4D planning context if the building model is complex and mixed with multiple domain information. Using the BIMserver, however, planners can focus on their interested entities to define plan tasks by automatically retrieving related parts from IFC model server. This effective and efficient working approach can be easily achieved in the client ends by developing related IFC-compliant features to identify smart objects and related project plan information in IFC models. Because IFC data structure has defined data types like IfcWall, IfcRoof, IfcDoor, etc. (BuildingSmart, 2013), the identification of related smart objects and project plan information from the BIMserver has no barriers to be realised. The adoption of BIMserver into the 4D planning groupware will also get rid of the server development burden with few efforts to update original functions in the clients. The entity-based 4D planning groupware still can preserve existing functions and further create IFC-compliant features by using SOAP interfaces provided by the server.

3.2 Enabled VR technologies

VR technology wins wide acclamations in the AEC industry (Dawood et al, 2006; Woodard et al, 2009; etc.). It provides computer applications with added values such as improved HCI, better information visualization, sense of 'presence', improved simulation, etc. (AIG, 1994). Besides these benefits, it also has potentials to facilitate collaboration in the 4D planning process. Adopting these excellent features, a distributed 4D-VR environment is able to empower a collaborative planning team to create a robust construction plan. This section discusses available technologies for VR-enabled 4D groupware creation.

A range of software tools and packages are available for 4D-VR application development. Following the interactive definition method, a created 3D building model is needed as input to foster a shared planning context. In terms of 3D building modelling, CAD systems such as 3D Studio MAX, AutoCAD, MicroStation, CATIA, etc. can be applied for 3D modelling. Latest BIM systems like Revit, Tekla, ArchiCAD, Digital Project, etc. provide even more powerful features to reach this aim. High level real-time graphics packages such as Multigen Creator, VEGA, EON, etc., are reported in both product modelling (Kim, 2001) and operational modelling (Li, 2003). Some popular low level computer graphics development kits like OpenGL and Direct3D have already widely applied in not only the AEC field but also other graphical intensive industries like mechanical engineering, gaming, etc. Recent research showed success using Direct3D in distributed 4D CAD creation based on the desktop platform (Zhou et al, 2009; 2012). Mainstream graphics cards like NVIDIA GeForce can support these 3D graphical technologies to create immersive effect based on an active stereo VR system (Belleman et al, 2001).

4D CAD studies are reported using different VR platforms. In accordance with the capability of producing immersive effect, VR platforms generally consist of three types: non-immersive VR (desktop VR), immersive VR, and semi-immersive VR (Woksepp and Tullberg, 2002). Correspondingly, their equipments are desktop PC, head mounted display (HMD) or cave automatic virtual environment (CAVE), and projector-based power wall. Almost all current 4D studies are based on desktop systems and can be considered desktop VR solutions suitable for individual applications. It was also acclaimed that the value of a CAVE in 4D construction planning lies in 'a tool to foster collaborative planning with improved communication among the various project planners' (Yerrapathruni, 2003). In view of limited space of CAVE system, it is still mainly suitable for individual work. At the same time, it is seen that projector-based power walls have the capacity to enable a group of audience working collaboratively. A good example is Construction Management Simulation Centre (BMSC) (Vries, 2004), which is dedicated to construction on-site training for collocated students in the VR environment. Given a network condition, the power wall based VR system can be applicable for both distributed and collocated collaboration in 4D planning.

Summarising these software and hardware utilities, it can be feasible to develop a distributed collaborative 4D-VR groupware system based on a semi-immersive power wall platform using active stereo projector and BIMserver connection. Commercially available BIM authoring tools can provide object-based IFC models inputted in the system, whilst low level graphics development kits can be applied for the 4D groupware development incorporating the depicted 4D CSCW design. The latter can also apply existing 4D systems, e.g Autodesk Navisworks since it fully supports VR configurations and functional extensions. Because of the requirements of IFC models from BIMserver, entity-based CAD models need to be converted into IFC models for the server application. Conversion methods can refer to relevant documents from CAD vendors, such as AutoCAD Architecture from Autodesk (Solihin, 2010). The network infrastructure can underpin the groupware for communication. The BIMserver-based 4D-VR groupware system can be applied for both collocated and distributed collaboration depending on planners' availabilities.

4. CO-STUDIO FRAMEWORK

On the basis of the foregoing discussions of 4D planning groupware, BIMserver and enabled VR technologies, the application framework of 4D-VR groupware system can be constituted by connecting a few of stand-alone 4D-VR systems as clients, which is named Interactive Studio (iStudio), with BIMserver through the Internet. A group of networked iStudio systems create Collaborative Studio (Co-Studio). Every single iStudio as a node in the Co-Studio network can support local planners for individual work or collocated collaboration whilst Co-Studio links geographically dispersed planners (in iStudio) for distributed collaboration. Co-Studio system architecture and its groupware application features are discussed as follows.

4.1 System architecture

Co-Studio can apply the server-client mode in its 4D groupware architecture. Accordingly, the groupware applications encompass a server-side application using the open source BIMserver and a few of client-side applications. The server-side application takes the responsibility of connecting the client-side applications for communication via the network. The client-side application provides planners with related functions to perform planning work and communicate with other online collaborators. Some third party utilities like MS Project can also run in the client side to support the groupware performance. Using Microsoft Windows as operating system, the Co-Studio system can be based on networked PCs with the extensibility of becoming networked semi-immersive VR systems. Each independent PC running the client-side application creates an iStudio system. Underpinned by the BIMserver connection, a few of iStudio systems can be connected into Co-Studio. The overall system architecture is illustrated in Figure 2.

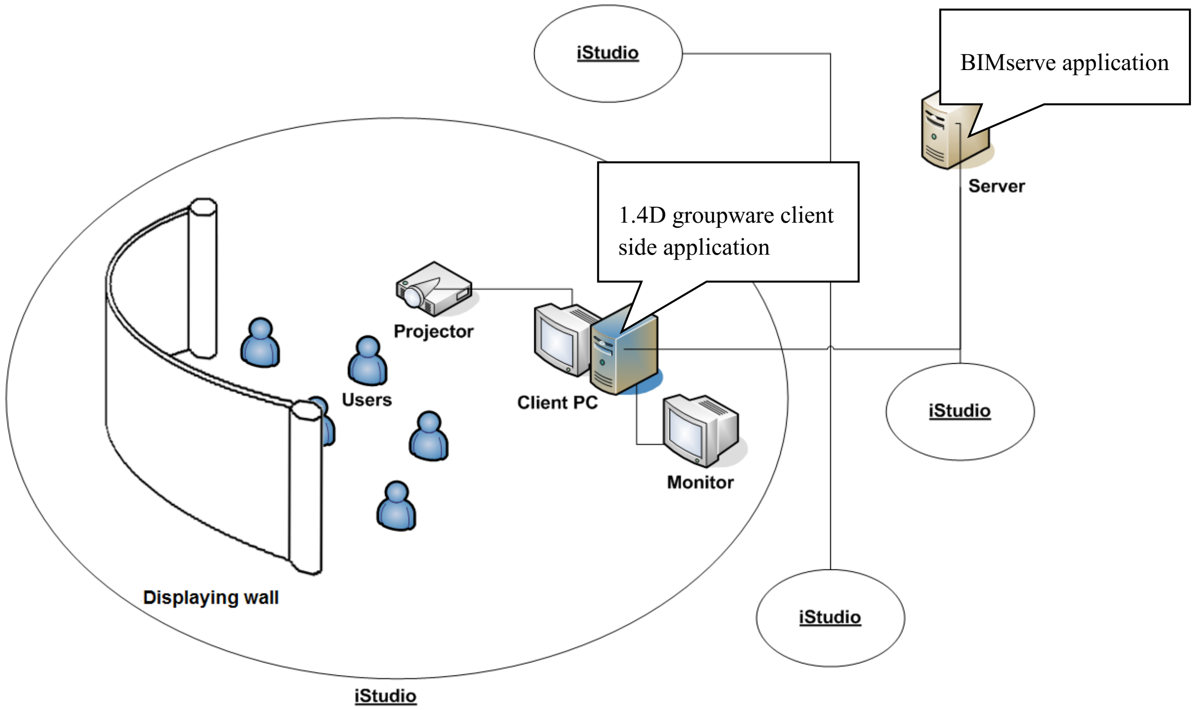


Fig. 2: iStudio and Co-Studio system architecture

Besides 4D groupware client-side application, the software in iStudio can adopt MS Office utilities like MS Project, MS Excel, etc. as well as third party video conferencing system. The 4D client-side application can support planning work while the MS Office tools are applied for recording planning and other nD modelling analytical results synchronously. Its basic hardware configuration is a standard PC connecting with multiple monitors. The multi-monitor in the system can provide planners with specific user interfaces of the 4D client-side application, MS Office, and videoconference. This hardware configuration can be further extended to a power wall based 4D-VR system using suitable projectors and graphics cards. Therefore, the user interface of 4D client-side application is possible to be projected onto a displaying wall to generate immersive effect. Based on seamless interoperability of Windows messages and object linking and embedding (OLE) technology in the Windows system, the 4D client-side application can exchange information with MS Office utilities synchronously during planning and simulation process. In the network condition, online iStudio systems can communicate with each other for exchanging and integrating plan information, and conduct 4D simulation across the network for creating a robust construction plan.

4.2 Application feature

Application features are different between stand-alone iStudio and networked iStudio – the Co-Studio based on different platforms (Table 1). On the desktop PC platform, iStudio is suitable for individual planning work. The existing CSCW design of co-navigate, co-sort, co-plan and co-simulate can be only performed by individuals without collaborators. In this circumstance, individual planners can conduct navigate, sort, plan, and simulate in their local iStudio for planning. The outcome of this individual planning is a finished plan and simulation without integration from other planners. The finished plan can still be outputted synchronously during planning and simulation process using Windows OLE technology. Co-Studio on the networked desktop PC platform can be applicable for distributed collaboration among individual planners. Online collaborators can fully conduct the designed CSCW activities to co-navigate, co-sort, co-plan and co-simulate for real-time collaborative planning.

Table 1: Application Matrix of iStudio and Co-Studio

Type	Desktop PC	Power wall
iStudio	Individual application	Collocated group collaboration
Co-Studio	Distributed individual collaboration	Distributed group collaboration

Taking the advantage of power wall, the application of iStudio and Co-Studio can be available for a group of people. In the offline condition, iStudio can accommodate collocated planners and other stakeholders in the same place for collaboration. Its similar application example is reported in live projects such as Walt Disney Concert Hall (Goldstain, 2001). Nevertheless, this kind of collaboration only exists in oral communication among stakeholders. Planners still need to perform their own work separately without involving CSCW and data integration. In the online condition, positively, Co-Studio can enable planners to fully make use of designed CSCW for communication and data integration among geographically dispersed planners and stakeholders.

Compared with CIFE iRoom (Fischer et al, 2002), the proposed Co-Studio has unique features in both system architecture and application. Besides the significant differences of 4D groupware application and Internet availability using BIMserver, another difference between Co-Studio and iRoom lies in iStudio. The iRoom applies Local Area Network (LAN) to achieve data exchange among 4D CAD and other MS Office utilities supported by several computers, whilst iStudio can utilise Windows OLE technology to realise synchronous data transfer between the groupware and MS Office in the same computer. Apparently, the former needs more financial investment on multiple computers whilst the latter only utilise one computer to achieve the same aim, and thus be lightweight and affordable. In terms of application feature, iRoom is applicable for individual application and collocated group collaboration, whilst Co-Studio is more flexible that can be any of applications listed in the application matrix.

5. CONCLUSION AND FUTURE WORK

The Co-Studio framework has potentials to create a distributed 4D-VR environment for real-time collaborative construction planning underpinned by BIMserver. Through the methodology analysis of current construction simulation, the paper highlighted applicable collaborative 4D planning approach – the interactive definition method with BIMserver to be adopted into the Co-Studio groupware development. From application and constructional perspectives, it discussed BIMserver adoption and relevant VR technologies as well as a power wall based semi-immersive VR platform for the Co-Studio creation. On the basis of these discussions, the framework of Co-Studio and iStudio was proposed and analysed from system architecture and application features. Co-Studio and iStudio as networked and stand-alone 4D-VR systems are able to accommodate both individual and group as well as collocated and distributed users for advanced collaborative 4D planning though BIMserver connection. This convenience also implicates unique excellence in low cost, lightweight, and flexible system configuration compared with CIFE iRoom. Their prototype implementations will be conducted to verify its effectiveness and usability. Moreover, their industry project validation is anticipated being available in the near future.

6. REFERENCES

Advanced Interfaces Group (AIG) (1994) Survey of Virtual Reality Activity in the United Kingdom, Department of Computer Science, University of Manchester. available at: http://www.agocg.ac.uk/reports/virtual/27/27.pdf, accessed 5 Jan 2013

Belleman, R., Stolk, G., Vries, B. (2001) Immersive Virtual Reality on commodity hardware, Proceedings of the 7th annual conference of the Advanced School for Computing and Imaging.

BIMserver, Open source building information modelserver (2013) available at Bimserver.org, accessed 25 Jan 2013

Chau, K., W., Anson, M., and Zhang, J., P. (2005) 4D dynamic construction management and visualization software: 1. Development, Automation in Construction, Volume 14, Issue 4, August 2005, pp512-524

Collier, E. and Fischer, M. (1996) Visual-based scheduling: 4D modelling on the San Mateo County Health Centre, Proceedings of the 3rd ASCE Congress on Computing in Civil Engineering, Anaheim, CA.

Dawood N, Scott D, Sriprasert E., and Mallasi Z. (2005) The virtual construction site (VIRCON) tools: An industrial evaluation, ITcon Vol. 10, Special Issue From 3D to nD modelling, pg43-54, http://www.itcon.org/2005/5

Dawood, N. Marasini R and Dean J. (2006) VR-Roadmap: A vision for 2030 in the built environment, CONVR 2006, Construction application of VR, Florida, USA, 3-4- Aug, 2006.

Fischer, M., Stone, M., Liston, K., Kunz, J., Singhal, V. (2002) Multi-stakeholder collaboration: The CIFE iRoom. International Council for Research and Innovation in Building and Construction. CIB w78 conference 2002. Aarhus School of Architecture, 12 – 14 June 2002

Froese, T. (2003) Future directions for IFC-based interoperability, ITcon Vol. 8, Special Issue IFC - Product models for the AEC arena, (2003) 231-246, available at http://www.itcon.org/2003/17, accessed 5 Jan 2013

Hendrickson, C. (1998) Project Management for Construction, Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, PA l52l3. Available from: http://www.ce.cmu.edu/pmbook/

Heesom, D. and Mahdjoubi, L. (2004) Trends of 4D CAD applications for construction planning. Construction Management & Economics, 22, 171-182.

Industry foundation classes IFC2x edition 3 technical corrigendum 1, BuildingSMART International Ltd. (2007) available at http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/index.htm, accessed 5 Jan 2013

Issa, M., Rankin, J., Christian, J. and Permberton, E. (2007) Using interactive workspaces for team design project meetings. 7th international conference on construction applications of Virtual Reality. Pennsyvania State University, October 22-23, 2007

Jongeling, R. and Olofsson, T. (2006) A method for planning of work-flow by combined use of location-based scheduling and 4D CAD , Automation in Construction, In Press, Corrected Proof, Available online 24 May.

Kamat, V.R., Martinez, J., C. (2003) Automated generation of dynamic, operations level virtual construction scenarios, ITCon 8 (2003) 65–82.

Kang, J., H., Anderson, S., D., and Clayton, M., J., (2007) Empirical Study on the Merit of Web-Based 4D Visualization in Collaborative Construction Planning and Scheduling, Journal of Construction Engineering and Management. Volume 133, Issue 6, pp. 447-461, 2007

Kim, W., Lee, H., Lim, H., C., Kim, O., Choi, Y., K. (2001) Visualized Construction Process on Virtual Reality, Fifth International Conference on Information Visualisation (IV'01), July 2001, pp. 0684

Koo, B. and Fischer, M. (2000) Feasibility Study of 4D CAD in Commercial Construction**,** Journal of Construction Engineering and Management Jul/Aug

Kam, C., Fischer, M., Hänninen, R., Karjalainen, A., Laitinen, J. (2003) The product model and fourth dimension project, ITcon Vol. 8 (2003)137-166, available at http://www.itcon.org/2003/12, accessed 5 Jan 2013

Li, H., Ma, Z., Shen, Q., Kong, S. (2003) Virtual experiment of innovative construction operations. Automation in Construction, 12(5): 561--575.

McKinney-Liston, K., Fischer, M., and Kunz, J. (1998) 4D annotator: a visual decision support tool for construction planners, in Wang, K.C.P. (ed.) Computing in Civil Engineering, Proceedings of International Computing Congress, Boston, 18–21 October, ASCE, pp. 330–41.

Mills, K., L. (2003) Computer-Supported Cooperative Work. Encyclopedia of Library and Information Science, Marcel Dekker, Inc., available at http://w3.antd.nist.gov/~mills/papers/120008706_ELIS_Batch6_R1.pdf, accessed 5 Jan 2013

Muramoto, K., Jentrud, M., Kumar, S., Balakrishnan, B., and Wiley, D. (2007) Emerging technologies in a tele-collaborative design studio between Pennsylvania State University and Carleton University. 7th international conference on construction applications of Virtual Reality. Pennsylvania State University, October 22-23, 2007

Solihin, W. (2010) Modeling for IFC with Autodesk Architecture, Autodesk, available at http://images.autodesk.com/adsk/files/modeling_for_ifc_with_aca_-_updated_for_aca2011.pdf, accessed 5 Jan 2013

Sriprasert, E. and Dawood, N. (2003) Multi-constraint information management and visualisation for collaborative planning and control in construction, ITcon Vol. 8, Special Issue eWork and eBusiness , pg. 341-366, http://www.itcon.org/2003/25

Succar, B. (2009) Building information modelling framework: A research and delivery foundation for industry stakeholders, Automation in Construction, Volume 18, Issue 3, May 2009, Pages 357-375

Tantisevi, K., and Akinci, B. (2007) Automated generation of workspace requirements of mobile crane operations to support conflict detection**.** Automation in Construction, Volume 16, Issue 3, May 2007, Pages 262-276

Tanyer, A., M., and Aouad, G. (2005) Moving beyond the fourth dimension with an IFC-based single project database, Automation in Construction, Volume 14, Issue 1, January 2005, Pages 15-32.

Vries, d. B., Verhagen, S., and Jessurun, A., J. (2004) Building Management Simulation Centre. Automation in Construction. vol. 13. no. 5. Elsevier. 679-687

Winch, G.M. (2002) Managing Construction Projects: An Information Processing Approach, Blackwell Science, Oxford.

Woksepp, S., Tullberg, O. (2002) Virtual Reality in Construction – A state of the art report. Department of Structural Mechanics, Chalmers University of Technology, Göteborg, Sweden.

Woodard, P., Ahamed, S., Canas, R., and Dickinson, J. (2009) Construction knowledge transfer through interactive visualization, Learning by Playing. Game-based Education System Design and Development, Lecture Notes in Computer Science, Springer Berlin / Heidelberg, ISBN 978-3-642-03363-6, July 31, 2009

Yerrapathruni, S., Messner, J., I., Baratta, A., J., and Horman, M., J. (2003) Using 4D CAD and immersive virtual environments to improve construction planning. CONVR 2003, Blacksburg, VA.

Zhou, W., Heesom, D., and Georgakis, P. (2006) Designing a Distributed VR Environment for Collaborative Construction Planning. Proceedings of World Conference of Accelerating Excellence in the Built Environment (WCAEBE 06'). Birmingham, United Kingdom, 2006.

Zhou, W., Heesom, D., Georgakis, P., Nwagboso, C., Feng, A. (2009) An interactive approach to collaborative 4D construction planning, ITcon Vol. 14, Special Issue: Technology Strategies for Collaborative Working, pg. 30-47, http://www.itcon.org/cgi-bin/works/Show?2009_05

Zhou W., Georgakis P., Heesom D., and Feng X. (2012) A Model-based Groupware Solution for Distributed Real-time Collaborative 4D Planning through Teamwork. Journal of Computing in Civil Engineering, Vol. 26, Issue 5, September, pp597-611, 2012. ASCE. ISSN 0887-3801

PART V: BIM AND GIS: INTEROPERABILITY AND STANDARDS

BIM AND GIS FOR LOW-DISTURBANCE CONSTRUCTION

Rizal Sebastian, Michel Böhms & Pim van den Helm
TNO Technical Sciences, Delft, The Netherlands

ABSTRACT: *Construction and maintenance activities of bridges often bring negative impacts to the urban environment in terms of disturbance, traffic jams and disruptions, noise, dust, and air pollution. Lack of coordination between the stakeholders in strategic, tactical and operational construction planning process has been identified as a key factor behind these negative impacts. Attempts to solve this issue critically depend on an effective interoperability between ICT tools from the building domain (based on Building Information Model or BIM) and the urban planning domain (based on three dimensional Geographical Information System or 3D GIS). Research on the interoperability between BIM and GIS requires knowledge of Open BIM as well as Open GIS and their interconnection. Unfortunately, Open BIM and Open GIS have been developed separately and they have pursued different standards and technologies. Open BIM for civil infrastructure projects is still limited, especially due to the fact that the IFC open standard currently targets the building sector. Open GIS mainly relies on the use of GML/CityGML standard.*

This paper focuses on research to develop a solution for the interoperability of BIM and GIS, especially for the purpose of low-disturbance construction. It reports the on-going EU FP7 collaborative research project PANTURA. The preliminary achievements include a prototype solution that consists of: an architecture for the integration solution between BIM and GIS data and tools; an Application Domain Extension (ADE) that connects BIM data from the bridge with the computational parameters on disturbance in a GIS-based planning tool Urban Strategy; a configuration of open-source Deegree 3D model server; and a query interface between the model server and the decision-support tool. The prototype solution is verified using two case studies: on-site assembly of a new bridge on La Palma island, Spain; and refurbishment of existing bridges in Rotterdam, the Netherlands.

KEYWORDS: *BIM, GIS, interoperability, decision-support tool, low-disturbance construction, bridge project, urban environment.*

1. INTRODUCTION

Lack of coordination in strategic and operational construction planning process has been identified as a key main factor behind the negative impacts of urban infrastructure projects (Sebastian et al., 2013). In order to enable the clients, designers, builders, and project managers to explore all possible planning, design and engineering solutions for low-disturbance construction, there is an urgent need for integrated modelling and analysis of the construction objects (e.g. bridges) and the surrounding areas that will be affected by the construction or maintenance activities. There are many existing tools and software applications (e.g. urban planning tool, risk management tool, building design tool, structural engineering tool), yet each of them only addresses a particular scale level and supports a specific process. Most existing tools are not compatible with each other, and the users are facing either great redundancy or crucial loss of information when attempting to integrate the knowledge across different domains and project stages. Solving this issue critically depends on the interoperability between information modelling tools from the building domain and the urban planning domain. Unfortunately, certain gaps in the interoperability of data and tools between Building Information Model (BIM) and Geographical Information System (GIS) still remain.

This paper addresses research on the interoperability of BIM and GIS for low-disturbance construction, especially regarding bridge projects in the city. It reports an on-going EU collaborative research project titled PANTURA in the 7th EU Framework Program for Research and Technology Development. It mainly discusses research on ICT instruments focusing on the development of interoperable BIM and GIS based solutions by connecting: 1) an existing tool Urban Strategy for interactive spatial planning based on meta-data of urban situation; 2) the Building Information Model (BIM) of a bridge that contains project-specific technical and planning data; and 3)

Citation: Sebastian, R., Böhms, M. & van den Helm, P. (2013). BIM and GIS for low-disturbance construction. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

a decision-support tool to be used by the project stakeholders when considering the priorities and consequences of possible decisions in relation to low-disturbance sustainability indicators.

The structure of the following sections of this paper reflects the research methodology as adopted in the PANTURA project. It can be summarized as follows.

- First, state-of-the-art review is carried out with the focus on issues of GIS and BIM interoperability; functionalities and required further development of an existing tool Urban Strategy; and comparative analysis to select the feasible and most optimal solution for the interoperability of BIM and GIS based on open standards.
- Second, the user requirements for the BIM-GIS instruments for low-disturbance construction are defined. The definition is made based on interactive feedback from the other research work packages in the PANTURA project. Then, the development of the new prototype solution is described particularly with regards to the four abovementioned main aspects.
- Third, the preliminary outcomes are verified and demonstrated in two case studies of real bridge projects in Spain and the Netherlands. The case studies address the design and planning for new and existing bridges.
- Finally, conclusions and discussions are presented regarding the current achievements and remaining issues (both technical and user-related), and the applicability of the proposed solutions for other projects.

2. STATE-OF-THE-ART REVIEW

2.1 Urban Strategy tool for interactive planning

Supporting ICT tools have an important role during the planning and design of low-disturbance construction projects. A number of interactive urban planning tools are currently available, for instance: Urban Simulation, Interactive Urban Design, Value Lab, Urban Explorer, and PlanYourPlace, StrateGIS Urban Developer, AGISwlk, SEMANCO, and tools for environmental impact assessment (Chan, et al. 1998; Vries et al., 2005; Halatsch et al., 2008; TII, 2012; Steiniger, 2012; Seijdel et al., 2011; Yaakup et al., 2004; Madrazo, 2012; Gontier, 2010). These tools rely on GIS almost entirely and have very limited interference with BIM of the buildings or other construction objects.

The Urban Strategy tool is considerably unique compared to other existing tools. It is a tool that combines the 3D interactive planning functionality with impact analysis capability. It can visualize two or three dimensional model of the urban area including the graphical information of traffic, noise, air quality, CO2, ground quality, and safety condition. It is able to analyse and compute across the various urban aspects. Each aspect is computed using a specific model, e.g. traffic model, noise model and air quality model. The data regarding the various aspects are integrated by means of: a 3D data store and a communication layer that bridges between the various computational models. This will enable the decision-makers to take the necessary measures before, during, and after the construction of the new bridge (Duijnisveld et al., 2010). The 3 main components of the Urban Strategy are shown in Fig 1.

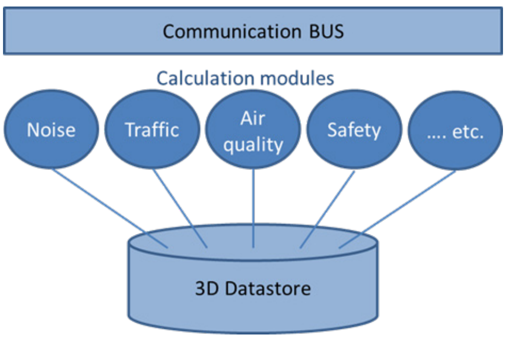


Fig. 1: The main components of Urban Strategy tool.

These components are: 1) the communication layer (BUS); 2) a set of calculation modules for different parameters (e.g. calculation module for traffic, calculation module for noise, calculation module for air quality); 3) the data store. The BUS works following the principle of trigger mechanism. After a computing process, the BUS received a signal regarding the changes made to certain types of data, and subsequently notifies the subscribed calculation modules that the relevant data have been changed or renewed. The data store is basically an Oracle database. It is also possible to store simple geometric data, for instance based on import from CityGML, but these cannot contain the CityGML structure. Despite its already comprehensive functionalities, further developments are needed to make possible the input-output relation with BIM model (e.g. the BIM model of a bridge). Moreover, an improved mechanism to retrieve and represent the relevant information for certain stakeholders is needed to support multi-actor decision-making and coordination processes that is crucial to achieve the low-disturbance objective.

2.2 Open-standard based approaches for connecting BIM, GIS and Urban Strategy

Research and discussions on the interoperability between BIM and GIS require knowledge of the interoperability between different BIM models –the so-called "Open BIM", as well as the interoperability between different GIS models –the so-called "Open GIS". Open BIM has a long history in ISO STEP (Standard for the Exchange of Product model data) and buildingSMART IFC (Industry Foundation Classes). At this moment, many experts acknowledge that IFC is the best available standard information structure that uses ISO STEP languages (EXPRESS, SPFF) for its compliant content representation (ISO, 2004; ISO, 2002). Current effort under the term IFCforInfra aims to broaden the scope of IFC to cover civil infrastructure (Yi et al., 2011). Practical solutions for civil infrastructure are currently sought by modifying the existing IFC models for AEC. Another option is to use proprietary interfaces on top of advance technologies like web services (W3Schools, 2013). Regarding the platform for BIM data, an examples of open-source software (OSS) applications for BIM servers is the BIMServer as an OSS variant on top of the highly scalable OSS Berkeley key-value DBMS by Oracle (BIMServer, 2013; Seltzer et al, 2012).

Open GIS mainly relies on the use of GML/CityGML standard from the Open Geospatial Consortium (OGC, 2013). GML/CityGML is completely built in the mainstream web/XML-technology: the content is in XML that is compliant to XSD (XML Schema Definition) information structures. GML also provides a very flexible extension mechanism known as Application Domain Extension (ADE). In the latest CityGML version 2, existing ADEs can be integrated – in other words: some parts in the earlier version of CityGML that were only available as ADE are now an integral part of the standard. Regarding the platform for GIS data, compliant client software applications and tools are available, for instance the OSS Deegree Server that can store GML features and support open-source database engines PostgreSQL/PostGIS as well as relational DBMS/Spatial Engine (PostgreSQL, 2013).

Based on the existing concepts, in principle, in the PANTURA research project, three main strategies were identified for the interoperability of Open BIM and Open GIS data:

- Keep them separate: Essential integration between BIM and GIS to meet minimum requirements will reply on the capability of the end-user applications, i.e. import/export between BIM and GIS.
- Consolidate in Open BIM and use Open GIS as an open data provider: Open GIS is used as the provider for data to be included in BIM.
- Consolidate in Open GIS and use Open BIM as open data provider: GIS represents 'the bigger picture' wherein a variety of data sources –among others BIM with regards to building objects– can be integrated.

When open-standard based approach is used (thus, relying on Open BIM and Open GIS), in theory, there are three possible scenarios to connect the Urban Strategy tool with Open BIM and Open GIS for the purpose of low-disturbance construction projects (Fig 2).

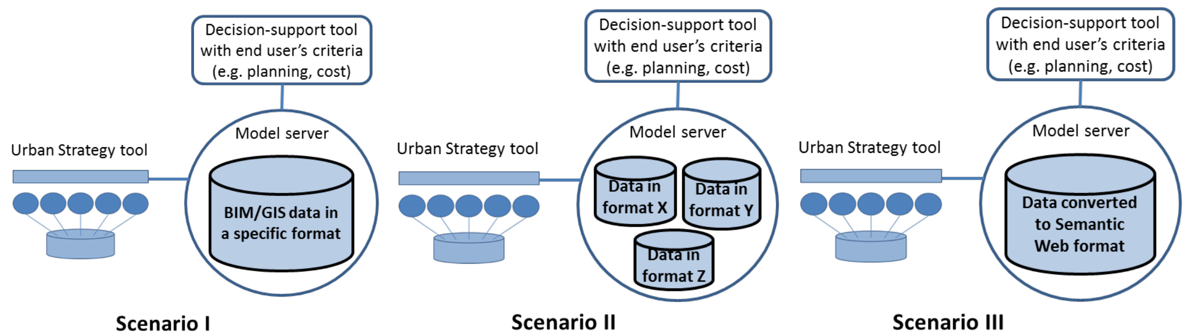


Fig. 2: Investigated scenarios to connect the Urban Strategy tool with Open BIM and GIS data.

In the Scenario I, all available and relevant BIM and GIS data are converted based into a certain format on a selected open standard. The converted data are then stored in a server. This scenario can be further specified into:

- Scenario I-a where IFC is the selected open standard and the open-source BIMServer or similar is used as the model server for data and applications (BIMserver, 2013).
- Scenario I-b where CityGML is the selected open standard and the open-source Deegree 3D server or similar is used as the model server for data and applications (GeoServer, 2013).

In the Scenario II, the data are stored in their original formats. The conversion only takes place when specific subsets of data are required to be used by certain calculation modules. This scenario can be based on COINS open standard. Here COINS serves as the controlling mechanism over different data formats. COINS is a Dutch initiative to develop a flexible BIM open standard applicable to improve the object-oriented content of the communication transfers according to Systems Engineering (SE). SE is used to formulate the functional specification with explicit specified requirements that can be matched with the expected or measured performances of the actual construction object (COINS, 2013).

In Scenario III, all relevant data are upgraded towards a semantic level. An RDF data server (W3C, 2013) can carry out this conversion to generate a semantic model. In this scenario, various open standards can be used and the interactions between them can take place on the semantic level. For instance, BIM IFC data can be converted to ifcOWL and then stored in the RDF server. Similarly, GIS CityGML data could be converted to the so-called CityRDF.

3. DEVELOPMENT OF BIM–GIS–URBAN STRATEGY INTEROPERABILITY SOLUTION FOR LOW-DISTURBANCE CONSTRUCTION

3.1 User requirements

The PANTURA research project aims to support the stakeholders to plan a low-disturbance bridge construction project by using an ICT tool. These stakeholders are thus considered as the end-users of the ICT tool. This ICT tool mainly consists of 2 parts: the End-User Application (EUA) and the integration platform of BIM – GIS – Urban Strategy. The EUA thus becomes the interface that is visible for and operational by the end-users, and therefore should be able to support the end-users in defining and combining their decision criteria, and assign the weighing factors when necessary, referring to the generic set of Key Performance Indicators (KPIs) for low-disturbance construction and the decision level (i.e. political, strategic, tactical, operational). Based on the development of the KPIs and the priority list derived from Europe-wide benchmarking (PANTURA, 2011), the EUA focuses the following KPIs, for which the input is provided by the BIM and/or GIS data:

- Worker safety, which is asserted in BIM as the “WorkerSafety” property in the bridge model.
- Resident safety, which is asserted in BIM as “ResidentSafety” property in the bridge model.
- Noise, which is calculated based on noise source points in Urban Strategy dataset as “MaxNoiseLevel” property for each building in the surroundings of the bridge construction site.
- Mobility, which is calculated based on the information of capacity and Intensity of roads at the construction site and surrounding areas. This information is derived from traffic intensity level, which serves as input to the Urban Strategy dataset.

3.2 Architecture for interoperability

After the exploratory research on three possible scenarios for open-interoperability as discussed in previous section and shown in Figure 3, in the PANTURA research project, it was decided to elaborate solutions based on Scenario I-b, i.e. CityGML is the selected open standard and the open-source Deegree 3D server or similar is used as the model server for data and applications. Three main preferences behind this decision are:

- The preference to convert all types of data to one open-standard format for compatibility with the from the EUA; and therefore, Scenario II where various original formats are maintained was excluded.
- The preference to rely on an operational (‘up-and-running’) open-standard; and therefore, Semantic Web format has been excluded since much research is still needed.
- The focus on multiple civil infrastructure objects integrated in their urban areas; and therefore, CityGML has been considered more practical than IFC. Moreover, export to CityGML format from Urban Strategy model is already supported.

In order to proceed with the selected Scenario I-b, four key steps are necessary to achieve the solution for data/model interoperability. These steps are shown in Fig. 3.

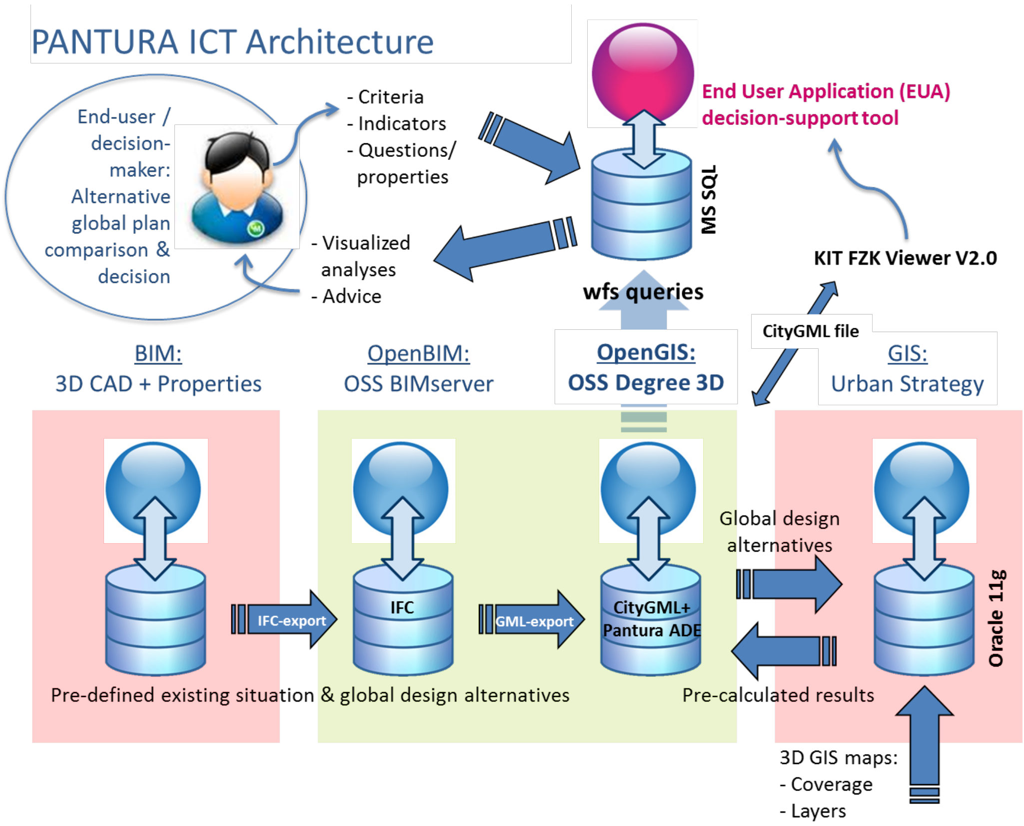


Fig. 3: BIM – GIS interoperability architecture developed in the PANTURA research project.

A set of design and construction solutions for the bridge, including their properties, are modelled in BIM using different software as selected by the client, designer, engineer, or contractor. The 'native' BIM models are exported to open-standard IFC models. These IFC models are then then transformed into CityGML format. The properties are handled by the PANTURA ADE (which is explained in the next section). This CityGML models and other GIS data are stored in the Deegree 3D model server (an open GIS server, which is explained in the next section). All information structures and semantics are based on CityGML, and the used syntax is XML. The Urban Strategy tool can use CityGML data in the Deegree 3D model server to make calculation/analysis of disturbance impacts. The calculation results are then fed back to the model server. The EUA accesses the information in the Deegree 3D model server via fully-standard queries of Web Feature Services (WFS) and stores the data in its native data storage (Microsoft MS SQL) for further processing. The EUA performs analysis of the data based on the KPIs, decision-making criteria and weighting factors as selected by the end-users.

3.3 Open standards and Application Domain Extension (ADE)

Operationalizing the architecture for interoperability requires interfacing solutions utilizing open standards (i.e. IFC and CityGML) as well as Application Domain Extension (ADE). As mentioned in previous section, CityGML is used in the PANTURA research project as the intermediate language for all data derived from various sources (BIM, GIS and Urban Strategy dataset). CityGML is an extension of GML (Geography Mark-up Language), which is a language using a XML structure for describing geographical information. CityGML contains more detailed geographical information, and particularly describes urban objects in three dimensions including the inter-relations between these objects. For the purpose of supporting decision-making in low-disturbance bridge construction projects, CityGML 2.0 is chosen. In CityGML 2.0, a bridge has become part of the standard; this is not the case in the 1.0 or 1.1 version.

In order to 'connect' CityGML and IFC, an ADE is needed. The level of taxonomy and semantics in CityGML is lower than in IFC, and hence, directly translating (exporting) the data from IFC to CityGML will result in loss of information. By extending the CityGML standard via an ADE to match IFC data types and hierarchy, the loss of information can be reduced significantly. In the PANTURA research project, the BIM IFC model of a bridge is translated to a CityGML model with help of the PANTURA ADE.

Along with its function to support the translation from IFC data to CityGML data, the PANTURA ADE also contains dedicated properties that are relevant for analysing disturbance impacts during bridge construction. This is needed to overcome the limitations of CityGML in supporting custom properties of an object-type. Using the PANTURA ADE, certain values –depending on the design and construction scenarios– can be assigned to the properties of the bridge models. The Urban Strategy tool can then be used for analysing and comparing the disturbance impacts of these scenarios.

3.4 Open-source model server

Based on the proposed architecture and the use of open standards in the PANTURA research project, the model server should meet the following criteria: is open-source, able to handle CityGML models, able to facilitate queries by the Urban Strategy tool and the End-User Application, and accessible via the internet. The available open-source model servers, which fulfil these criteria, are Deegree 3D and GeoServer (Deegree, 2013; GeoServer 2013). Both servers can store geospatial (CityGML) data, can be queried via the internet using Web Feature Service (WFS), and are java-based software. Since the functionalities and performance of both servers keep growing and changing along with the on-going development, it is hardly possible to draw a scientific comparison before selecting the most optimal solution. In the PANTURA research project, it was decided to experiment with the Deegree 3D server. Configuring the Deegree 3D server to support CityGML models and the Urban Strategy dataset was done through the following steps:

- Creating a database: The Deegree 3D server is capable of using different types of geospatial databases, but a database has to be created manually before use. For the purpose of disturbance analysis during construction in the PANTURA research project, a Postgres database (an object-relational database management system which can hold multiple databases) with the addition of PostGIS (for the geospatial part) is set-up.
- Setting up a Java Database Connectivity (commonly known as JDBC, which enables Java programs to execute SQL statements) within the Deegree 3D server: This connection will rely on the location of the server as well as the port that holds the database, database name, username, and password of the database user. When the database is available, the Deegree 3D server needs to be further configured to use this database as the location where ‘features’ (i.e. objects and properties of the GIS models) are stored.
- Setting up a feature store within the Deegree 3D server: A feature store can take a database as its storage containers. Transactional queries can also fill the database with new features. During the creation of the feature store, the Deegree 3D server generates a set of SQL statements to configure all necessary tables, based on a schema that identifies all existing feature types. This schema is the CityGML schema as described in the previous chapter along with the ADEs (i.e. PANTURA ADE). After these SQL statements have been performed, it is then possible to upload a CityGML file to fill the feature store.
- Adjusting the used WFS version (an optional step, only when necessary).

4. CASE STUDIES TO VERIFY THE PROTOTYPE SOLUTIONS

4.1 Case study of on-site assembly of a new bridge in Los Sauces, La Palma, Spain

A relevant case for the application of BIM and GIS to plan low-disturbance construction project was provided by ACCIONA and Government of the Canary Islands, both from Spain, which are partners in the PANTURA consortium. The case of the new bridge in Los Sauces town was to construct a new pedestrian bridge along the main road at a key location in the Los Sauces town. Since there was only one main road which connected the two parts of the town, the construction of the pedestrian bridge should be done in such a way without closing this main road; or if road closing is inevitable, then the closing time and disturbance should be minimized. For this reason, as well as other long-term sustainability considerations, it was decided to build a lightweight bridge of Fibre Reinforced Composite (FRP) material through off-site prefabrication. ACCIONA was the selected contractor, and it prefabricated the FRP beam of the bridge at its factory in Madrid. The FRP beam of the bridge was then transported to La Palma, prior to the on-site assembly process. The case study focused on deciding the most optimal scenario for the one-site assembly of the FRP bridge.

Two scenarios for on-site assembly were defined in the case study:

- On-site assembly scenario I: The FRP beam is transported from the port to the project site by truck. When the truck arrives to the project site, a crane located next to the road and in one side between the abutments is ready to lift up the beam from the truck and to place it on the abutments. In order to carry out this activity, one of the two road lanes is closed temporarily because the truck parks on the road lane next to the construction site. Once the beam is placed on the abutments, the truck can leave and the road can be opened again. The whole process would take maximum 2 hours. The noise level is reasonably low, but there would be some traffic disturbance during the transport from the harbour to the construction site.
- On-site assembly scenario II: Scenario II differs from scenario I by the use of a helicopter for transporting the FRP beam the harbour to the construction project site. The distance from the harbour to the project site by helicopter is about 14 km. No traffic disturbance would be experienced during the transport, yet standard and additional safety factors when transporting a load with helicopter must be taken. The noise level is high, and the road needs to be closed completely during the process for safety reasons.

The experimental application of BIM, GIS and Urban Strategy tool in this case can be summarised as follows.

- Preparing BIM and GIS data, including: development of BIM model of the bridge in a native 3D CAD software (ArchiCAD); inclusion of properties related to disturbance, i.e. construction time; export to IFC, based on the agreed IFC structure; and import and adjustment of 3D GIS map of La Palma into Urban Strategy tool.
- Generation of construction planning including 2 possible scenarios for on-site assembly process, inclusion of properties related to disturbance, i.e. worker safety and resident safety.
- Defining the disturbance parameters and stakeholders' decision criteria in the Urban Strategy tool, i.e. noise, traffic; and in the EUA, including the data source to compute these parameters, based on 3D GIS map, BIM IFC model, and statistics.
- Facilitating the data and application interoperability by developing and implementing an ADE that connects BIM data from the bridge with the computational parameters on disturbance in Urban Strategy; and facilitating the inter-connection between Urban Strategy tool and EUA on Deegree 3D server.
- Calculation and analysis through: executing Urban Strategy calculation process on each of the 2 possible scenarios for on-site assembly process; analysing the Urban Strategy calculation results (i.e. the disturbance impacts of each scenario) based on the end-user criteria using the EUA; and presenting the analysis results at a decision-making meeting involving the stakeholders (demonstration session involving other PANTURA consortium partners).

4.2 Case study of refurbishment of existing bridges in Rotterdam, the Netherlands

As partners in the PANTURA consortium, the City of Rotterdam from the Netherlands provided a relevant case for low-disturbance construction project, and NCC AB from Sweden provided a BIM model of an existing bridge to be used for experiment of BIM and GIS interoperability in this case. The Willems Bridge, which contained a series of bridges, was one of the key connections between the Northern and Southern city parts. There was a real plan to improve the Willems Bridge due to mid-life refurbishment; the fulfilment of European requirement of the passage height under the bridge for water transport; the increase of traffic load; the extension of public transportation route; and the area development agenda of the City of Rotterdam. Low-disturbance construction was of a high –if not the highest– priority considering the strategic location of the Willems Bridge for both shipping and road transportation, any disruption due to the bridge refurbishment project will bring huge negative economic, social and political impacts to Rotterdam.

For the case study of the PANTURA research project, the city of Rotterdam developed three conceptual scenarios, which were assessed using BIM, GIS and Urban Strategy tool in order to recommend a strategy for low-disturbance construction.

- Scenario I covers refurbishment and strengthening of existing two bridges (the Willems Bridge and the Koninginne Bridge), including a new public transport route over the existing bridges.
- Second II comprises renovation of an existing bridge (the Willems Bridge) and construction of a new bridge next to the Koninginne Bridge.
- Scenario III proposes relocation and extension of an existing bridge (the Willems Bridge) and construction of a new bridge. This proposal aims to introduce a new and efficient public transport route simultaneously with elevating, extending and relocating the Willems Bridge.

Regarding scenario II and III, a BIM model based on an existing bridge was used as a fictional example of a new bridge to be positioned parallel to the Koninginne Bridge. This BIM model was originally developed by NCC AB using Tekla software. The actions taken during the experimental application of BIM, GIS and Urban Strategy tool in this case were similar to the first case study (La Palma case). The difference was that the project scenarios affected the choice for design solutions –instead of choice of assembly solutions as discussed in the first case.

5. CONCLUSIONS AND DISCUSSIONS

This paper reports on-going research in the EU collaborative project PANTURA, especially addressing investigation of BIM and GIS interoperability for the purpose of planning and decision-making of low-disturbance bridge construction projects in the city. The research started with a literature study to examine the possible concepts. The main result of this literature study was ICT architecture to solve BIM-GIS interoperability as shown Fig. 3 in the Section 3. This architecture was then verified using two case studies as described in Section 4. During the experiment, new or improved solutions to facilitate the interoperability were developed and technical issues were resolved. The research activities, which reflected the conceptual ICT architecture, are shown in Fig. 4. The achievements and issues at each research step are concluded in Table 1. Within the PANTURA project, these activities were part of Work Package 3 (WP3), which sub-divided into 2 tasks, i.e. T3.1 and T3.2.

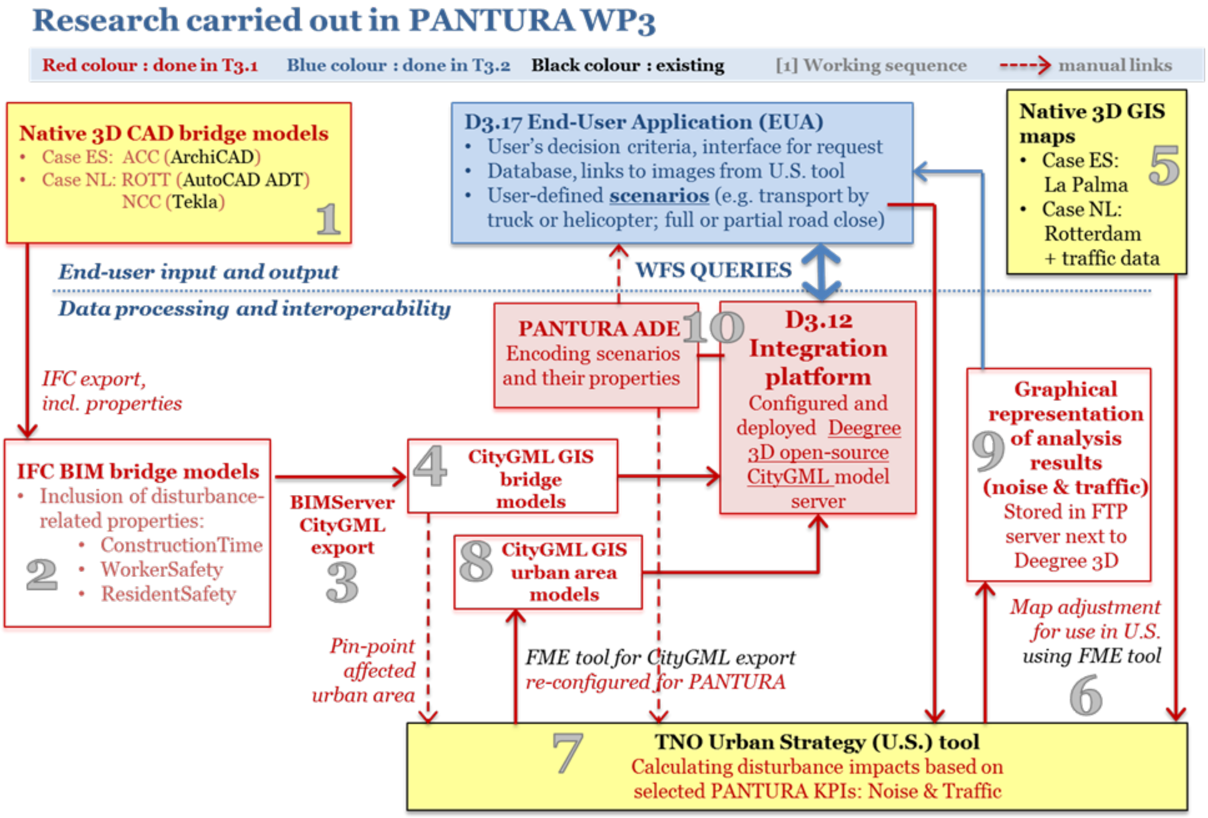


Fig. 4: Current research activities and achievements.

Table 1: Achievements and issues at each research step.

Research step	Achievements made	Issues tackled
1	Consolidated the 3D CAD models of the bridges (new and existing).	Model structure and IFC export from native software.
2	Exported IFC models of the bridges, and inclusion of disturbance-related properties in IFC parameters: ConstructionTime, WorkerSafety, and ResidentSafety.	Naming and consistency of the IFC parameters.
3	Exported CityGML models of the bridges using the PANTURA-CityGML export function that is a plugin for the open-source BIMServer.	Coordinate systems and conversions.

4	Stored CityGML models of the bridges on open-source Deegree 3D model server; pin-pointed affected urban area in the city.	Storage configuration of the model server.
5	Consolidated 3D GIS maps of the cities, including existing traffic data model that was available for Rotterdam.	Completeness and compatibility of the native GIS maps; representation of the explicit shapes involved (like solids or multi-surfaces for objects); availability of relevant data model or statistics for disturbance analysis (e.g. traffic, noise).
6	Adjusted / corrected / combined GIS maps including disturbance-related information as input for Urban Strategy tool – done with help of the existing FME tool (available on market).	Generation of traffic data model for case study La Palma – Spain.
7	Calculated disturbance impacts (i.e. noise and traffic) for 2 case studies.	Determining noise sources and measurements; processing traffic data models.
8	Output CityGML models of the affected urban area including the calculation results from Urban Strategy – export from Urban Strategy model to CityGML model was done with help of the existing FME tool (available on market).	Re-configuration of the FME tool for CityGML export according to PANTURA purposes.
9	Visualised output of Urban Strategy analysis results (e.g. graphical representations of noise level, traffic flow and congestion in the area depending on various construction scenarios).	Storing the images on an FTP server connected with the End-User Application (EUA).
10	Configured and deployed open-source Deegree 3D model server including PANTURA ADE. The PANTURA ADE keeps the configuration and allows users to define queries based on encoding the scenarios and properties.	Configuring the Deegree 3D server for PANTURA schema, data format, and database/storage location; pre-defining the WFS queries; fixing technical bugs in the server; setting-up hardware to host the PANTURA Deegree server (accessible on www.modelservers.org/deegree-pantura/).

Based on the lessons learned from the current research, the following discussions can be presented to address the practical implementation of the solutions and recommendations for future research:

- The PANTURA approach can be used to connect a 3D BIM model and a 3D GIS map. The BIM model can be generated by any CAD/BIM software with IFC export functionality. Thus, this approach can be generalised for implementation in other projects / by other parties.
- The originality of research in PANTURA is found in the attempt for open-interoperability of BIM and GIS, particularly for the purpose of decision-making in low-disturbance urban projects. The challenge of open-interoperability is very high since it must face 4 fronts of complexity at the same time, namely: open BIM; open GIS; connection with an analytical tool, such as the Urban Strategy; and connection with a decision-support tool comprising end-user's criteria and disturbance key performance indicators. Within the context of this challenge, no straight forward connectivity can be found; and therefore, the selected ICT architecture as discussed in this paper consists of a number of export / conversion steps. The selected ICT architecture has been made operational and verified in two case studies, yet neither this paper nor the PANTURA project intends to proclaim that this is the most effective and efficient route towards the BIM-GIS open-interoperability. More research is needed to build scientific arguments to support (or oppose) the selected approach.
- One of the innovative solutions which can be derived from experiment in PANTURA is the use of Deegree 3D server to store and make available CityGML data. The server configuration, including the particular purpose for scenario analysis on disturbance impact, has been registered in the PANTURA ADE. This can become an input for future standardisation regarding properties of data model, server configuration, and standardised query definition.

6. REFERENCES

BIMServer (2013). Open source building information model server, www.bimserver.org (last accessed on 1 February 2013).

Chan R., Jepson W. and Friedmann S. (1998). Urban Simulation: an innovative tool for interactive planning and consensus building, *Proceedings of the American Planning Association national planning conference,* Boston, Massachusetts, USA.

COINS (2013). COINS reference manual (Willems, P. and Schaap H. editors), http://www.coinsweb.nl/wiki/index.php/Reference_Manual (last accessed on 1 February 2013).

Deegree (2013). Deegree 3D, http://wiki.deegree.org/deegreeWiki/deegree3/deegree3D (accessed on 1 Feb 2013).

Duijnisveld M., Kievit M. de and Schelling A. (2010). Urban Strategy keeps your city in the move, *Proceedings of Colloquium Vervoersplanologisch Speurwerk, Roermond,* The Netherlands. [in Dutch]

GeoServer (2013). What is GeoServer, http://geoserver.org/display/GEOS/What+is+Geoserver (accessed on 1 Feb 2013).

Gontier M., Mörtberg U. and Balfors B. (2010). Comparing GIS-based habitat models for application in EIA and SEA, *Environmental impact assessment review,* Vol. 30, 8-18.

Halatsch J., Kunze A., Burkhard R. and Schmitt G. (2008). ETH Value Lab: a framework for managing large-scale urban projects, *Proceedings of 7th China urban housing conference,* Chongqing, China.

ISO (2002). *ISO 10303-21:2002 Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure,* ISO, Geneve.

ISO (2004). *ISO 10303-11:2004 Industrial automation systems and integration -- Product data representation and exchange -- Part 11: Description methods: The EXPRESS language reference manual,* ISO, Geneve.

Ji Y., Beetz J., Bonsma P., Nisbet N., Katz C. and Borrmann A. (2011). Integration of parametric geometry into IFC-Bridge, *Proceedings of the 23th forum Bauinformatik,* Cork, Ireland.

Madrazo L., Sicilia A. and Gamboa G. (2012). SEMANCO: Semantic tools for carbon reduction in urban planning, *Proceedings of 9th European conference on product and process modelling (ECPPM),* Reykjavik, Iceland.

OGC (2013). CityGML, http://www.opengeospatial.org/standards/citygml (last accessed on 1 February 2013).

PANTURA (2011). *Comparative analysis of best practices: review of existing methods and development of an indicator suite for PANTURA goals, Project report D6.4,* EU FP7 Project PANTURA.

PostgreSQL (2013). About PostgreSQL, http://www.postgresql.org/ (accessed on 1 Feb 2013).

Sebastian R., Claeson-Jonsson C. and Di Giulio R. (2013 forthcoming). Implementation of MEAT for low-disturbance bridge reconstruction projects, *Construction innovation: information, process, management,* Vol. -, No. -, xx - xx.

Seijdel R., Dullemond A. and Schevers H. (2007). StrateGIS 3DSS: collaborative 3D decision support for urban development, *Proceedings of Seminar on the playful city – serious gaming for sustainable urban development,* Delft, The Netherlands.

Seltzer M. and Bostic K. (2012). *Berkeley DB: The architecture of open source applications* (Brown A. and Wilson G., editors), Online Self-Publishing ww.lulu.com.

Steiniger S., Poorazizi M. E., Bliss-Taylor C.A.M., Mohammadi E. and Hunter A.J.S. (2012). PlanYourPlace: merging social networks and participatory GIS for participatory planning, *Proceedings of FIG working week,* Rome, Italy.

TII (2012). Urban Explorer – Applied research project of Swedish ICT Interactive Institute, https://www.tii.se/projects/urbanexplorer (last visited on: 25 January 2013).

Vries B. de, Tabak V. and Achten H. (2005). Interactive urban design using integrated planning requirements control, *Automation in construction,* Vol. 14, 207– 213.

W3C (2013). Reference Definition Framework RDF, http://www.w3.org/RDF/ (accessed on 1 Feb 2013).

W3Schools (2013). Introduction to Web Services, http://www.w3schools.com/webservices/ws_intro.asp (accessed on 1 Feb 2013).

Yaakup A.B., Johar F., Maidin M.A. and Ahmad E.F. (2004). GIS and decision support systems for Malaysian development plan studies, *Proceedings of international conference on spatial planning and decision support systems,* Kuala Lumpur, Malaysia.

7. ACKNOWLEDGEMENT

This paper refers to the on-going collaborative research project titled PANTURA, co-funded by the European Commission within the EU FP7 programme (www.pantura-project.eu). The authors are lead researchers in this project. The case study data are provided by ACCIONA Infraestructuras SA, NCC AB, Government of the Canary Islands, and the City of Rotterdam, all of which are partners in the PANTURA consortium.

THE ARCHITECTURE DEVELOPMENT FOR THE INTEROPERABILITY BETWEEN BIM AND GIS

Tae Wook Kang & Chang Hee Hong
Korea Institute of Construction Technology, Korea

ABSTRACT: *The purpose of this study is to propose a scalable architecture that can be supported via the BIM (Building Information Modeling) on a GIS (Geographic Information System) platform for information interoperability between various heterogeneous systems such as BIM, GIS, and FM (Facility Management). This platform requires the acquisition of information from various data sources such as IFC (Industry Foundation Classes) and DBMS (Database Management System) if a use case for facility management, energy management, and design evaluation needs to be implemented, followed by a transformation of the information into appropriate information that can represent the perspective suitable for the use case.*

IFC may be considered a method for information interoperability, but it has a limitation in representing information in the perspectives of the use cases. Unlike the support of information interoperability based on the existing IFC, we would like to approach the problem of GIS- and BIM-based information interoperability by separating the problem in terms of geometry and property information. The geometry information is transformed into a simplified surface model from the IFC geometry information for that visualization of a number of objects represented in the GIS. The information required for the use case perspective is extracted and transformed from the property information by utilizing ETL (Extraction, Transform, and Load). ETL is a technology that extracts, transforms, and loads information from a variety of data sources and has been used for OLAP (Online Analytical Processing) function implementation via data mining in the management engineering arena to represent perspective-oriented information. In this study, we have applied ETL from the perspective of BIM.

For this purpose, we have reviewed the related study trends and derived a general use case of BIM on a GIS platform. Further, component architecture is designed to implement the use case as well as a Star Schema to represent information according to the perspective for the development of a data warehouse. On the basis of these, BGP architecture is proposed for implementing the ETL concept using BIM on a GIS platform. Furthermore, a use case for the facility management of Korea Institute of Construction Technology is implemented as a prototype to show the usefulness of the proposed architecture. Thus, in this study, we demonstrate that information required from the perspective of project stakeholders can be interoperated effectively.

KEYWORDS: *BIM, GIS, integration, interoperability, perspective representation, ETL*

1. INTRODUCTION

Interoperability recently performed by extracting and transforming required information from the perspective of each project stakeholder through GIS-based BIM has emerged as a big issue. GIS and BIM are similar in terms of modeling space information (one is for the outdoors, and the other for the indoors) as well as have common use cases for each system. For example, location-based information query and object management or path finding, which have been the traditional use cases in GIS, have also been utilized conceptually in the case of BIM. In particular, if each system's use cases can be operated in an integrated manner, effective urban facility management can be possible. For integrated use case implementation, effective interoperability between GIS, BIM, and FM should be supported at the platform level.

In order to facilitate seamless information operability in the construction sector, the BuildingSMART Association has developed and standardized the IFC and put in a significant amount of effort to accept requirements from the industry. IFC is an integrated model schema for construction information designed by an

Citation: Kang, T. W. & Hong, C. H. (2013). The architecture development for the interoperability between BIM and GIS. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

object-oriented method to integrate all the information required by project stakeholders from the big BIM perspective.

Through the information model integration attempts via this IFC, we have ultimately tried to achieve the required objectives. However, issues have arisen while solving the interoperability problem in practice. For example, during the information exchange between heterogeneous systems or commercial modeling software using IFC, some information loss or change has been reported (Lim Jae-In, 2008.6).

In order to support interoperability via the IFC, there should be no problem in parsing the IFC model and interpreting the meaning for information extraction and loading followed by the information exchange. To achieve this, IFC should accept the integration of information models managed and modeled by heterogeneous systems and there should be no confusion while exchanging information via IFC in terms of the semantic points of views. Currently, the IFC model is a building-oriented information model, which is on the way to improvement and advancement. IFC may accept general information. However, it is not easy for IFC to support a system's information models for specialized purpose utilization. Moreover, the information models created by some commercial modeler software were developed for a commercial purpose to keep their formats closed to the public, which makes IFC difficult to accept. Further, the development philosophy of these models for the information model schema was different from that of the IFC, which makes IFC compatibility relatively difficult.

The purpose of this study is to approach to the BIM-based information interoperability problem from a practical viewpoint unlike the direction of supporting the information interoperability based on the existing IFC. To this end, the ETL concept, which was widely utilized in the field of management engineering, was applied, thereby implementing a supporting architecture for effective information interoperability between heterogeneous systems such as BIM, GIS, and FM, and developing the prototype. Through such heterogeneous systems, in this study, we demonstrated effective interoperability of the required information from the perspectives of the project stakeholders.

In this study, information to be interoperated is divided into two categories:

1. Geometry information representation: When a user logs in to a GIS server, the BIM object geometry that is represented to the GIS viewer for a client should be a surface model, which is represented between LOD (Level Of Detail) 100 and LOD 200 specified in the AIA (The American Institute of Architects), taking the performance into consideration.

2. Property information exchange: Properties required only by the logged account from the user's viewpoint shall be displayed when a specific facility is selected in the BIM viewer, taking into consideration the perspective seen by the project stakeholders and information convenience.

2. RESEARCH OBJECTIVE

In this study, an architecture in which data were extracted from different heterogeneous systems such as BIM, GIS, and FM database using ETL was designed, and its prototype was developed. The extracted data were transformed into the required forms before being presented to a user. To this end, scalable information interoperability supported by the BIM-GIS-based architecture model was presented.

This architecture used the ETL solution for extracting and processing the required information from various heterogeneous systems. To validate the usefulness of the proposed architecture, simple facility management use cases were implemented. Information stored in the BIM facility management database of Korea Institute of Construction Technology was extracted and processed using ETL so that the information could be checked by GIS via the BIM model. The model uploaded in the GIS was a surface-based model, which simplified a large-capacity BIM model and had an information detail degree between LOD 100 and LOD 200 specified by the AIA. By double clicking, we uploaded the BIM model to the additional viewer so that information details of more than LOD 300 could be checked. When a facility object included in the model was selected, the information extracted via ETL could be viewed.

Through this architecture, required information according to each use-case perspective was defined, processed, and extracted via ETL; thus, heterogeneous systems were interrelated cost effectively to form a data warehouse that could be utilized for information mining. ETL could provide various data sources and facilitated function expansion. The BIM object geometry information could be visualized quickly by the simplified surface model.

The rest of this paper is organized as follows: Section 3 reviews the current study on the interoperability of BIM and GIS. This includes the use cases and platform architecture as well as ETL. In Section 4, we described the system architecture designed on the basis of the information given in the previous section. The architecture is designed to support the proposed use cases. A system is developed by referring to the architecture design, and a simple prototype program is demonstrated to show the implementation of the facility management use cases of Korea Institute of Construction Technology. The last section presents the conclusion and future research.

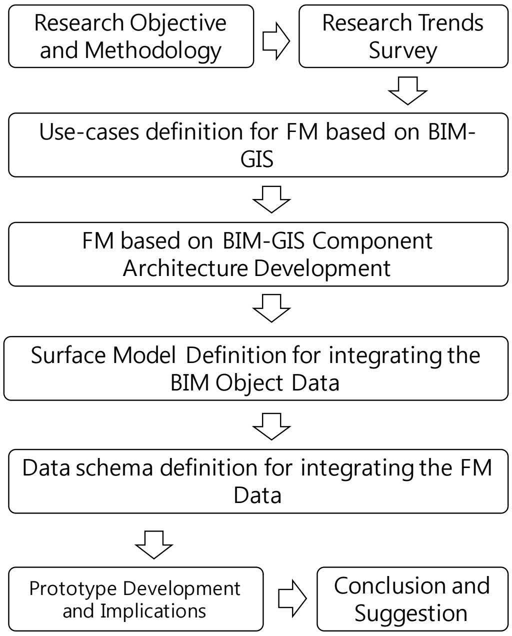


Fig. 1: Research Flow

3. CONVENTIONAL APPROACHES

3.1 CityGML Domain Extensions and Web service-based approaches

Hijazi proposed the mapping methodology to extract the utility the information by using CityGML Application Domain Extensions (Hijazi I, 2011). As a study about the integration between BIM and GIS, there was a study of the GeoBIM to extend GIS data by using CityGML and Open source-based BIM server (Laat R. D, 2010.11).

As the another approach to integrate the data, there was the web service-based integration study to manage the urban data management by using CityGML, WFS (Web Feature Service) and 3D Viewer(Lapierre A, 2007). Döllner researched the integration method to integrate the urban information of GIS, CAD and BIM by using web service supported by ONUMA system (Döllner, 2007). Burcu studied the ontology structure and navigation method to resolve the use-cases between CAD and GIS (Burcu A, 2008.3).

As described above, most of the studies used the CityGML Application Domain Extensions or Web Service to import IFC or CAD data and the research to integrate the external data for the special purpose such as FM information related to GIS-based BIM is not enough.

3.2 Spatial Data Warehouse and ETL-based approaches

SDW (Spatial Data Warehouse) is a system that adds a 3D model of the required information from the user-case perspective to the existing data warehouse system. SDW has been studied for a long time consistently in the area of GIS. It supports analysis and decision making by storing non-volatile data that have the integration and temporal property according to a topic-centered space information and non-space property information (S. Chaudhuri, 1997). SDW is constructed on the basis of the space data extracted from heterogeneous systems such as the GIS and the Asset Management System. BIM is also focused on the re-utilization of the object information over a space and can be utilized effectively from the perspective of BIM interoperability. The SDW can be created and renewed in a topic-oriented manner via ETL.

ETL for the data managed in the FM can support extraction, transformation, and loading processes with respect to the data, such as manufacturer, manufacturing date, maintenance strategy, and maintenance date data, from the heterogeneous systems effectively. While loading the data, even if the numeric data are the same at the time of loading, they can have different meaning or representation methods depending on the project stakeholder’s or the user’s perspective.

During DW (Data Warehouse) construction, it is important to load only the required information by extracting file data used as the sources that were created from the heterogeneous DBMS or software used by the project stakeholders. The types of extracted data are space data such as geometry and non-space data such as properties. The figure given below shows the ETL process, which extracts, transforms, and loads data from various data sources. The spatial ETL plays the role of loading data, which were created in the data cleansing and transformation steps with respect to various sets of space data obtained from the heterogeneous systems, to the DW.

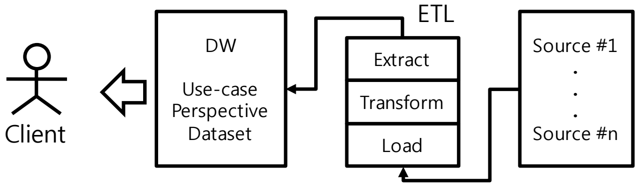


Fig. 2: ETL Process Concept Diagram

From the BIM perspective, space data, which were extracted and loaded through an ETL process from the data sources of various heterogeneous systems, should have a structure to assist the data analysis requirement with respect to the DW (Krivoruchko K, 2003).

For recent studies on ETL for buildings, a case study of the energy management system using ETL to perform extraction, transformation, and loading of data by Gökçe can be found (Gökçe H. U, 2011). Their study showed that a single integration information model was not suitable for the environment where each project stakeholder used a different database. This study proposed architecture in which the building information was extracted from data sources and sensor data including multi-dimensional data in order to avoid the abovementioned problem. The information was extracted from a wireless sensor network or CAD and managed in the data warehouse.

As described above, the SDW study, which was started in the GIS area, accounts for most of the DW and ETL-related studies. Although a study on ETL for buildings has been conducted recently, few studies have been performed on information interoperability in conjunction with the GIS.

4. SYSTEM DESIGN AND DEVELOPMENT

4.1 Use cases between BIM and GIS

When a system user wants to view specific information about any object, if unnecessary information is shown to the user other than FM information, the user may feel discomfort. Therefore, it is required to extract only the required data and present them to the user. In the situation wherein information, document files, and sensor information are managed additionally by the system databases, only the information required by a user should be viewed via the DW in which the required information is loaded, by interworking with a server. For example, when a facility administrator is logged in, he may check the status of facilities. On the other hand, a subcontractor of facility maintenance may want to view building structure information or maintenance history information. Data required from the user’s perspective should be queried to the DW, which holds the data beforehand via ETL, and displayed to the user. Information required from the user’s perspective should be defined beforehand by Star Schema.

The present study is focused on a method for an effective information exchange assuming that FM is a use case in order to support information interoperability between heterogeneous systems using GIS-based BIM. The utilized FM system assumes that information is managed by heterogeneous database systems or file-based systems. Taking this into consideration, the GIS-BIM architecture for FM should support the user’s information perspective. The use case scenario is as follows:

1. A user runs the GIS Client Program.

2. The user logs in to the GIS server. According to the login account, the information perspective is determined.

3. From the GIS server, the objects of GIS and BIM are loaded into the GIS Client Program.

4. The user selects a BIM object. The BIM viewer is run.

5. The user selects a specific facility object in the BIM viewer. Information regarding the login account perspective is acquired via a query to the DW. At this time, the DW stores the FM data that were constructed beforehand by Star Schema.

6. In the BIM viewer, the queried BIM object information is shown.

The following use-case diagram represented by the UML shows the above scenario:

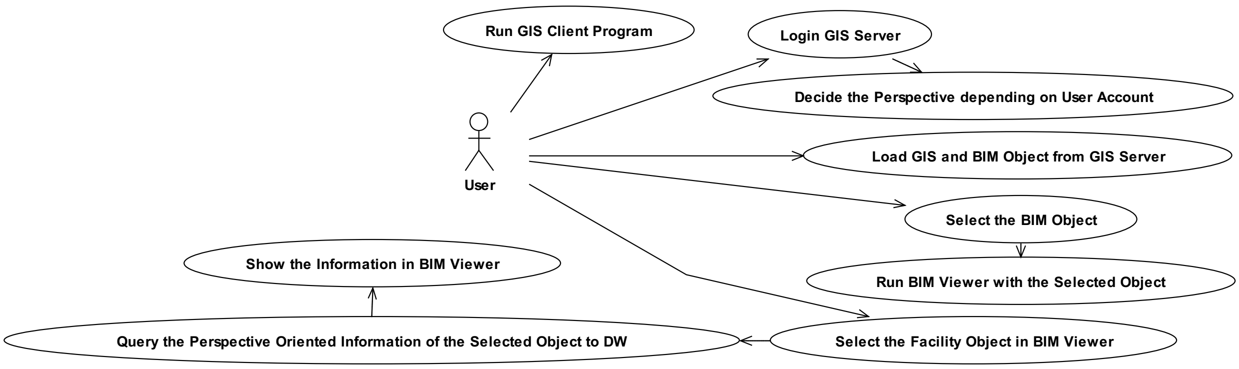


Fig. 3: Use-Case Diagram (UML)

Information types and levels from the user's perspective are defined below:

Table 1: Perspective-Oriented Information depending on FM User Account

No.	User Perspective	Information
1	Owner	Facility manager general, Space general information including space name, ID
2	Facility Manager	General management information, Space including structure/electric/mechanic element general information
3	Facility Subcontractor	Space general information, Space maintenance history

It was assumed that a user checks the information regarding the utilization of FM general information and space area mainly, while a facility management manager accesses the general management information and space, and general information regarding the MEP elements included in the space. On the other hand, it was assumed that a subcontractor for facility management will want to access the general information of the maintenance space and the history information of maintenance.

4.2 Component architecture with open source

The system architecture should consider the scalability and flexibility of the information exchange method in order to support interoperability. Taking this into consideration, the component architecture for supporting the BIM-GIS-based FM was designed using UML. To design a sustainable and cost-effective architecture, frequently used open sources were applied. In order to support fast visualization and search numerous BIM objects in three-dimensional space, our own BIM viewer was developed. In order to extract, process, and load the required data in the BIM data warehouse from the external FM DBMS, ETL open source Talend was used, and the transformation part was designed. The related component architecture is as follows:

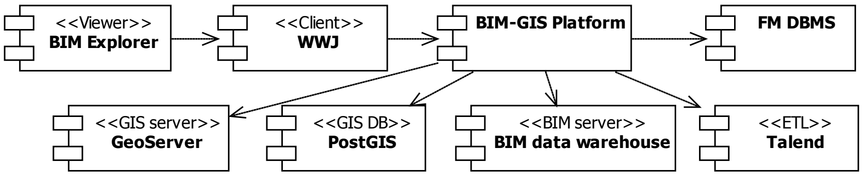


Fig. 4: BIM-GIS-based FM Component Architecture (UML)

The role of each component in the component architecture is as follows:

Table 2: BIM-GIS-based FM Component Description

No.	Stereo type	Component	Description
1	Client	WWJ (World Wind Java)	Java-based client program developed by the NASA and supports Google Earth-like UI and functions.
2	Viewer	BIM Explorer	Independently developed BIM viewer to visualize the object geometry using the light mesh-based surface model file by which IFC was transformed beforehand.
3	Platform	BIM-GIS Platform	Using GIS server, BIM server, and ETL module, it supports information interoperability between heterogeneous systems.
4	GIS Server	Geoserver	Open-source-based topography server that supports topography image or vector information streaming when WWJ client program is run.
5	GIS DB	PostGIS	Open-source program to support GIS-based space query when performing SQL query.
6	BIM Server	BIM Data Warehouse	BIM object-oriented extracted and loaded database of required information from the external heterogeneous systems, in which Star Schema was designed and placed beforehand according to a topic.
7	ETL	Talend	Required information is extracted and transformed from the external heterogeneous systems according to user’s perspective and loaded into the BIM DW.
8	FM DBMS	KICT FM DB	Excel-based database used for this study and created by Korea Institute of Construction Technology for FM.

4.3 Surface model for geometry representation

The IFC file, which is used as a BIM neutral file, is a flexible and scalable structure, but it has a problem that the file format itself is a heavy and complex structure. This problem is partly due to the fact that IFC contains phase information between objects as well as B-Rep geometry parameter information for geometry modeling. However, geometry information utilized over the GIS does not normally require geometry modeling, and a fast representation of numerous object geometry pieces of information is considerably important; hence, modeling-related information is not necessary. It is important for the GIS to represent geometry rapidly and appropriately in a three-dimensional space according to the distance of an observer view, by creating the LOD of objects beforehand.

Because of these reasons, in the present study, we converted mashes before they are used according to LOD in the B-REP geometry model included in the IFC. These files are managed in the server, and when the GIS client program requests this information, it is transferred to the client. The figure given below represents the structure of the surface model as a UML.

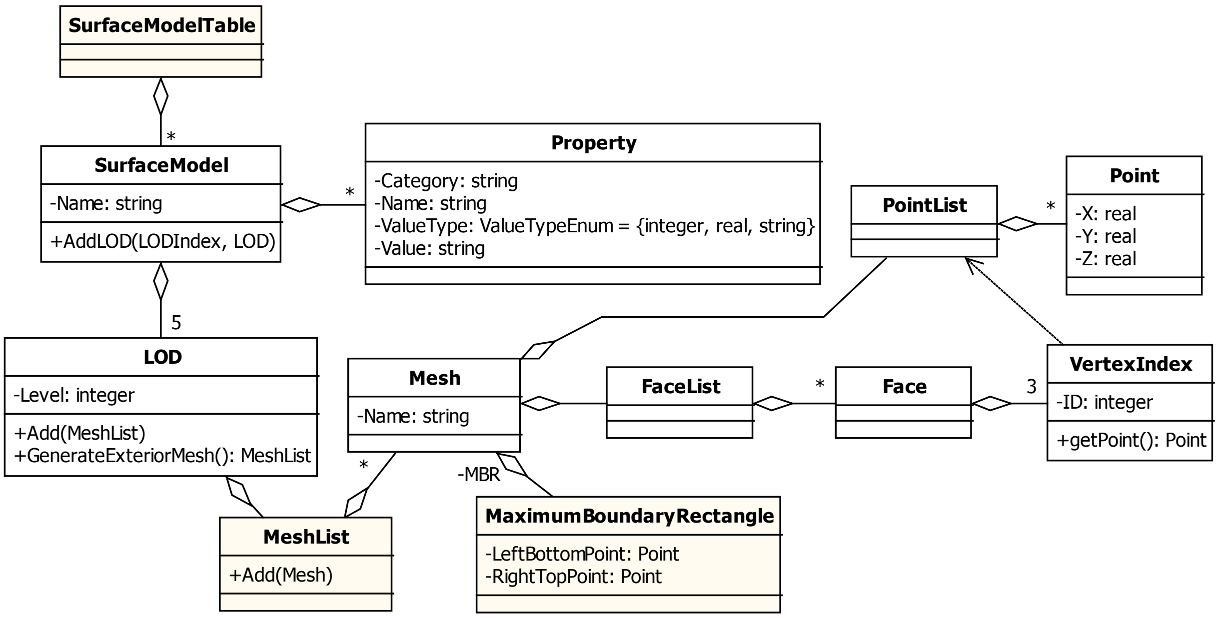


Fig. 5: Surface Model Structure for Geometry Representation in GIS

In order to create the surface model structure, using the developed IFC converter, five LOD levels were converted as a semi-automatic mode to meet the CityGML LOD level. LOD contains a number of meshes. A mesh consists of PointList, which manages the X, Y, and Z coordinates; FaceList, which manages Face consisting Mesh; and VertexIndex consisting Face. VertexIndex manages the corresponding Point ID in PointList.

Property manages the information category, property name, property value type, and property value. Property is extracted via the IFC converter from the BIM object after the store process.

The below describes the sequence diagram to create the mesh about LOD-2. To extract the exterior surfaces of the LOD-2 from the mesh, the screen buffer which is similar to the Z-buffer was used. The other LODs are created manually.

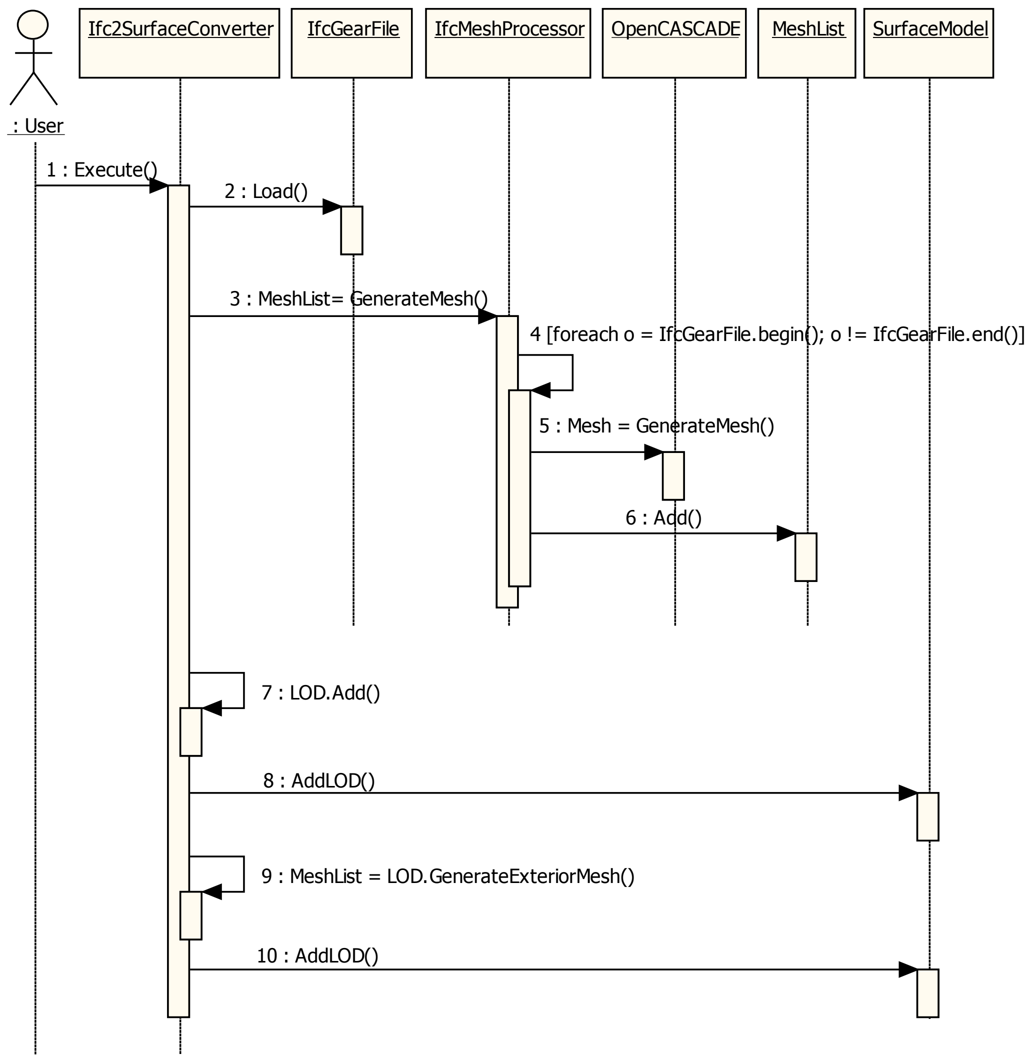


Fig. 6: Sequence diagram to create the Surface Model

4.4 Star Schema for properties exchange

Star Schema was developed for FM to support topic-based queries. Once the elements required for FM were analyzed, a dimension table and a fact table were designed on the basis of the DW components. Further, DW was constructed via BIM ETL so that the information required from the project stakeholder's perspective could be queried. As shown in the figure given below, five dimension tables and one fact table, according to the Star Schema format, were represented including the table name and the field names.

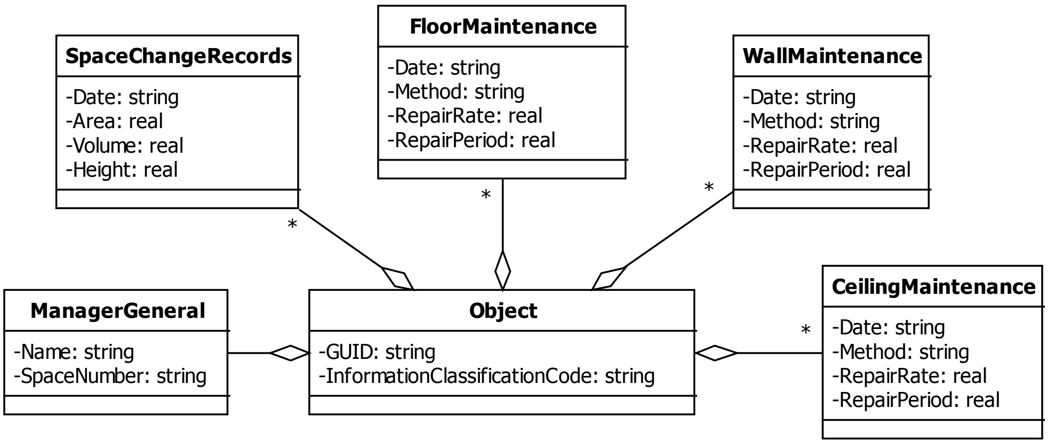


Fig. 7: Example of Table Design (Dimension Tables and Fact Table)

In order to process FM on the basis of BIM, we need to extract the facility management data stored in the dispersed databases followed by transformation into an easy format and store. This process is performed in ETL. Thus, property data extracted via data extraction, data transformation, and data load into the DW from various topography space data can help extract or analyze information from a project stakeholder's perspective. In this study, Talend open-source ETL software was used for the ETL engine. For data sources, files, databases, and open APIs were allowed to be used for extracting information.

4.5 System development

The process of system development is as follows.

1. Data Warehouse Star Schema Design and Development

2. FM Dataset Setting

3. ETL Process Development by using ETL with Talend

4. Set Information Perspective depending on User Account

5. Query Development of Perspective-Oriented Information about BIM Object

No. 1 is to define the Data Warehouse Star Schema, thereby creating a space to contain information so that OLAP can be performed to extract information by perspectives. In the Star Schema, the fact table should include the GUID of BIM objects, and on the basis of the GUID, information can be divided into many sets of information. If the information required by the user is the modification date and the maintenance details of an object among the past history of the object, the required information can only be queried to show the result to the user.

No. 2 is a step to set the required data source from the user's perspective to obtain the FM dataset.

No. 3 is a step to develop an ETL process to interwork with the BIM/GIS server and the FM dataset.

No. 4 is a step to set the information perspective according to user accounts.

No. 5 is a step to develop a perspective-oriented information query based on a BIM object when an object is selected.

5. CASE STUDY: BIM-GIS-Based KICT Facility Management System

A prototype system was developed by utilizing the BIM-GIS FM architecture designed in Section 4. The databases, which were interoperated with the present system for information interoperability, were Excel-based databases constructed for BIM-based FM located in Section 1 of the main building and the BIM objects modeled by Revit. The databases were constructed by referring to the existing managed documents. Note that Section 1 in the main building was an old building constructed in 2004; thus, maintenance history was managed by documents and drawings shown in the figure below, thereby having many pieces of missing information due to illegible handwriting. Further, it was difficult to obtain the maintenance history information according to a BIM object. Therefore, the facility maintenance history information was constructed on the basis of space.

Fig. 8: Documents and Drawing related to KICT FM

The database constructed in Korea Institute of Construction Technology for the FM was constructed within two months, a short period; therefore, it was primarily divided into structure data and maintenance history data for space and managed in Excel files. The classification code system for the facility object information was defined by referring to the construction information classification system published in 2006 by the Ministry of Construction and Transportation.

Table 3: KICT FM Space Data Item Description

No.	Item	Description
1	Information classification code	Space classification based on facility and configured as two-digit numbers
2	Space actual name	Actual space name
3	Space ID	Revit's Zone object ID and unique ID
4	Manager	Name of manager
5	Space number	To manage space room, facility manager assigned the number additionally
6	Space modification history information	Maintenance history information such as space modified date, space area, space perimeter, space volume, space ceiling height, and the number of occupants
7	Floor maintenance history information	Maintenance history information such as space floor finish, partial repair, repair rate, total repair, and final repair date
8	Wall maintenance history information	Maintenance history information such as space wall finish, partial repair, repair rate, total repair, and final repair date
9	Ceiling maintenance history information	Maintenance history information such as space ceiling finish, partial repair, repair rate, total repair, and final repair date

The above FM data were extracted, transformed, and loaded into the DW by the ETL process, and information was represented from the user's perspective.

The following figure shows the prototype system implemented.

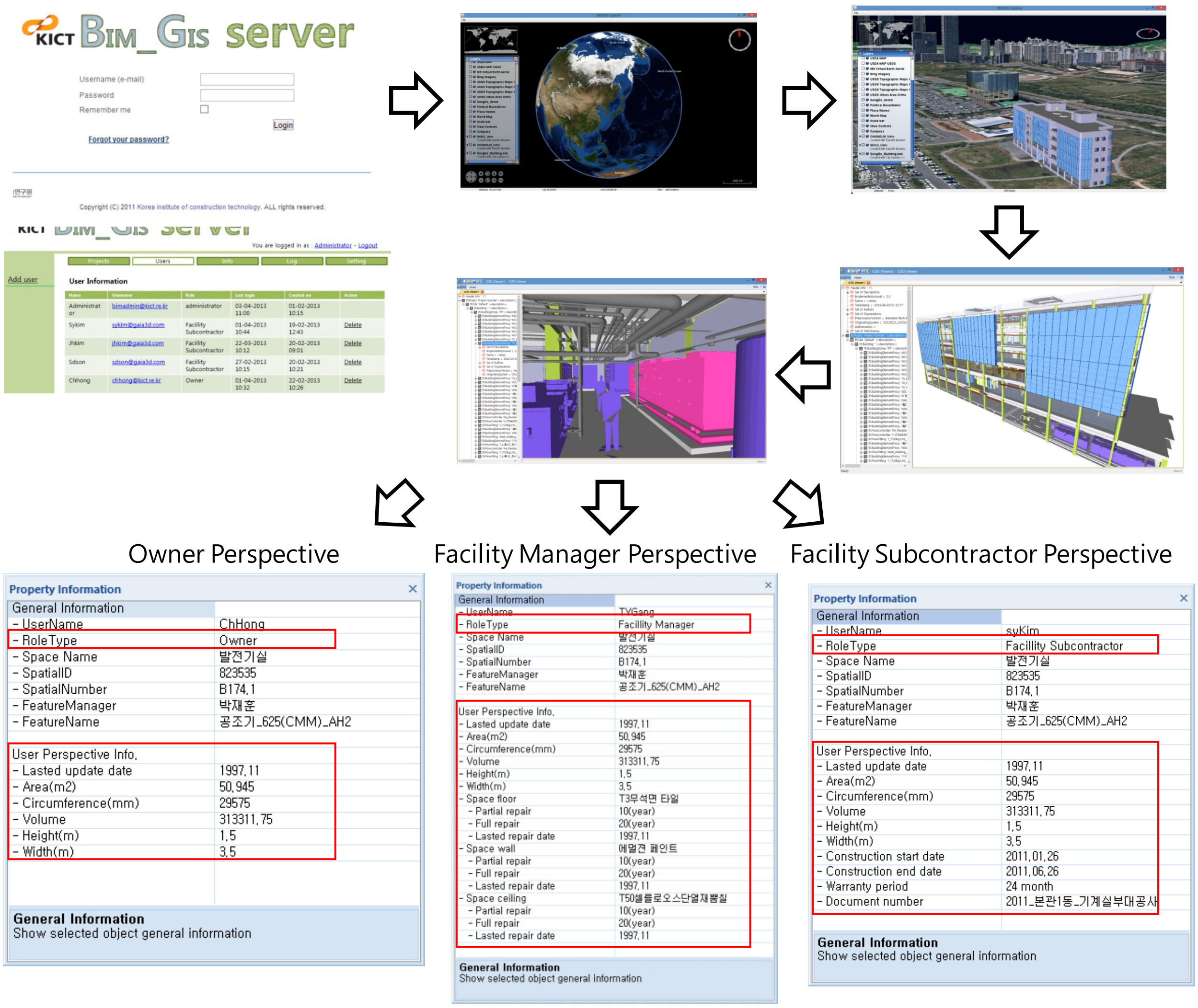


Fig. 9: FM Prototype System based on BIM-GIS Platform

6. CONCLUSION

In this paper, we proposed a scalable architecture for supporting interoperability between heterogeneous systems of BIM, GIS, and FM.

From the practical viewpoints of information interoperability, data were divided into geometry and property information so that the problem of GIS- and BIM-based information interoperability could be addressed. In order to visualize numerous objects represented over the GIS, from the IFC geometry information, a simplified surface model was converted while the property information was extracted and transformed to be utilized for obtaining the required information from the use-case perspective by utilizing ETL. Applying the open-source ETL (Extract, Transform, Load) solution, we designed an effective information interoperability supported architecture between heterogeneous systems of BIM, GIS, and FM and developed a prototype that implemented the FM use cases. Through them, the effective interoperability of required information from the project stakeholder's perspective could be verified.

In a future study, we intend to analyze the space data of a topic on the basis of the proposed architecture and the effect between the data sets through a linkage analysis between the space data previously analyzed and the other space data. We also intend to obtain the information required by using the query for decision making through data mining based on BIM.

7. ACKNOWLEDGEMENTS

This research was supported by a grant from a Strategic Research Project (Development of BIM/GIS Interoperability Open-Platform 2013) funded by the Korea Institute of Construction Technology.

8. REFERENCES

Burcu A., Hassan K., Anu P., Wu C. C. and Greg Fl. (2008.3). CAD and GIS Interoperability through Semantic Web Services, *ITCon*, Vol.13, 39-55.

Chaudhuri S. and Dayal U. (1997). An overview of data warehousing and OLAP technology, *Proceedings of ACM International Conference on Management of Data, ACM SIGMOD*, Vol. 26, No. 1, 65-74.

Döllner J. and Hagedorn B. (2007). Integrating urban GIS, CAD, and BIM data by service based virtual 3D city models*, Urban and Regional Data Management*, 629-635.

ESRI, Spatial data standards and GIS interoperability, *An ESRI White Paper*, 2003.

Gökçe H. U. and Gökçe K. U. (2012). Multi-dimensional energy management and optimisation system for energy efficient building operations, University of Alberta, Department of Civil & Environmental Engineering, Markin/CNRL Natural Resources Engineering Facility 9105 116th St, Edmonton, Alberta, Canada, T6G2W2.

Hijazi I. Ehlers M. Zlatanova S. and Becker T. (2011). Initial investigations for modeling interior Utilities within 3D Geo Context: Transforming IFC-interior utility to CityGML/UtilityNetworkADE, *Advances in 3D Geo-Information Sciences,* 95-113.

Jeon C. S., Lee D. W., You B. S., Lee S. J. and Bae H. Y. (2007.9). Non-duplication loading method for supporting spatio-temporal analysis in spatial data warehouse, *Journal of the Korea Institute of Spatial Information System*, Vol. 9, No. 2.

Korea Institute of Construction Technology. (2013). Development of Building Information Modeling Based Facility Management System of KICT.

Krivoruchko K., Golway C. A. and Zhigimont A. (2003). Statistical tools for regional data analysis using GIS, *A Proceedings of the ACM International Symposium on Advances in GIS*, 41-48.

Kyung M. J. (2009.12). Spatial data warehouse design and spatial OLAP implementation for decision-making of geospatial data update, Earth Information Engineering, Sejong University.

Laat R. D. and Berlo L. V. (2010.11). Integration of BIM and GIS: The development of the CityGML GeoBIM extension, *Advances in 3D Geo-Information Sciences*, 211-225.

Lapierre A. Cote P. (2007). Using Open Web Services for urban data management: A test bed resulting from an OGC initiative for offering standard CAD/GIS/BIM services, *Urban and Regional Data Management*, 381-391.

Lim J. I., Kim J. W., Kwon H. D., Yoon S. W., Kwon S. W. and Chin S. Y. (2008.6). IFC test between commercial 3D CAD application using IFC, *Korea Institute of Construction Engineering and Management*, Vol. 9, No. 3.

CHECKING SPATIO-SEMANTIC CONSISTENCY OF BUILDING INFORMATION MODELS BY MEANS OF A QUERY LANGUAGE

Simon Daum & André Borrmann
Technische Universität München, Germany

ABSTRACT: *One of the characteristic features of object-based Building Information Models is the close integration of geometric and semantic information into one model. This concept is thoroughly implemented by the Industry Foundation Classes (IFC), a comprehensive data model designed to provide a sound foundation for complex data exchange scenarios. Besides the provision of a large variety of data types for capturing the semantics of building elements and spaces, the IFC also makes it possible to define relationships between building elements and/or spaces, respectively. In particular, a spatial aggregation hierarchy can be modeled by successively applying the relationship IfcRelAggregates to space objects. However, no validation options currently exist to check whether the semantically defined aggregation hierarchy complies with the geometric setup of the individual spaces and building elements. This lack of consistency between the semantic and the geometric part of the BIM model may lead to serious data interpretation errors at the receiving end. To prevent this, we propose a new method for validating spatio-semantic consistency based on the usage of the Query Language for Building Information Models (QL4BIM) which on the one hand provides a means of accessing the IFC object model and on the other hand provides high-level spatial operators, such as Disjoint, Touching and Containing. The formulation of corresponding queries makes it possible to verify the spatio-semantic consistency of the IFC model. The paper discusses application scenarios and provides a number of relevant examples.*

KEYWORDS: *BIM, IFC, Topology, Validation, Consistency, Spatial Relationships*

1. INTRODUCTION

A Building Information Model (BIM) is a comprehensive digital representation of a building. It provides an information base which is employed throughout its entire lifecycle – from the early phases of conceptual design, to the detailed planning phase, and the realization and operation phases (Eastman et al. 2011). To cover the different demands involved during the various phases, a BIM provides not only the precise 3D geometry of the building, but also non-geometric information, such as the type of the individual components, their attributes (material, insulation etc.) as well as the relationships between them.

Numerous specialists are involved in the design and engineering of buildings. In order to achieve interoperability between the different software products employed, the Building Information Model has to be represented by an open, neutral data model. The Industry Foundation Classes (IFC) form such a neutral data model and provide comprehensive means for the semantic and geometric description of a building and its components (buildingSMART, 2012).

The IFC model is based on a strict separation between the semantic and the geometric description. In the semantic part, the building is described as an agglomeration of semantic entities with specific properties and relationships between one another. Each of the semantic entities can be associated with one or more geometric representations. This approach is well-suited for supporting the different demands of different users and/or applications on the geometric representation. However, this separation bears the risk that inconsistencies may arise between the semantic and the geometric description.

To provide an example we refer to the relationship *IfcRelContainedInSpatialStructure*, which is used to semantically describe the association between a spatial container and a building element contained in it. When exported erroneously by the authoring application, the resulting IFC model may contain space-element-pairs for which this semantic relationship is set, while the geometric representations associated with them do not actually fulfill the containment property. These kinds of inconsistencies are hard to detect and may lead to serious misinterpretations by the receiving application.

Citation: Daum, S. & Borrmann, A. (2013). Checking spatio-semantic consistency of building information models by means of a query language. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

In this paper, we introduce an approach for automatically checking the spatio-semantic consistency of IFC models. The proposed method is based on a query language which (1) provides access to the semantic part of the IFC model and (2) supplies spatial operators that make it possible to undertake a formal analysis of the geometric model.

2. RELATED WORK

Stadler & Kolbe (2007) discuss the problem of spatio-semantic coherence in the context of 3D city models and the associated standard CityGML. Similar to the IFC, CityGML also uses a dual data structure with a semantic and a geometric part. The main difference is that CityGML also provides ways of describing aggregation relationships on the geometric side, which is not the case for the IFC model. Accordingly the discussed approach focuses on aligning two aggregation hierarchies, while the approach presented here utilizes formal spatial analysis functionality for identifying qualitative spatial relationships between the geometric objects represented in IFC models.

The domain specific, open query language BIMQL (Mazairac & Beetz, 2013) can be used to select and update subsets in a building model. Although BIMQL does not provide an interface for checking spatio-semantic coherence, it provides powerful query functionality. The idea of query shortcuts, which is integrated in BIMQL, is revisited in QL4BIM. These shortcuts are partly static so that the IFC object model is simplified e.g. to pick up geometry representations. Secondly, QL4BIM also provides dynamic shortcut creation by end users to unburden the handling of complex traversals in the object model.

3. REPRESENTATION OF SEMANTICS AND GEOMETRY IN THE IFC

The IFC Model provides a comprehensive set of entities to describe the semantics and the geometry of a digital building model. It is maintained by the international organization buildingSmart and has been implemented by a large number of AEC software vendors. The currently release, version 4, has been published as ISO standard 16739. The majority of the ongoing governmental activities for promoting BIM for the public construction sector, such as the UK Government BIM Strategy or the US National BIM standard, heavily enforce the usage of this open data format for data exchange scenarios (bimtaskgroup 2013, NBIMS-US 2013).

The IFC model is defined by means of the data modeling language EXPRESS which forms part of the ISO standard STEP – STandard for the Exchange of Product model data (SCRA, 2006). The model is strongly object-oriented, providing a large number of classes (called entities) arranged in an extensive inheritance hierarchy. In addition, the IFC model applies the concept of objectified relationships, i.e. there are specific classes which need to be instantiated for representing relationships between entities. In this paper, we specifically focus on relationships with spatial semantics.

The IFC model follows a strict separation of the semantic description and the geometric representation (Fig. 1). The semantic part is the leading information structure in the IFC, proving main access to the model and all associated information.

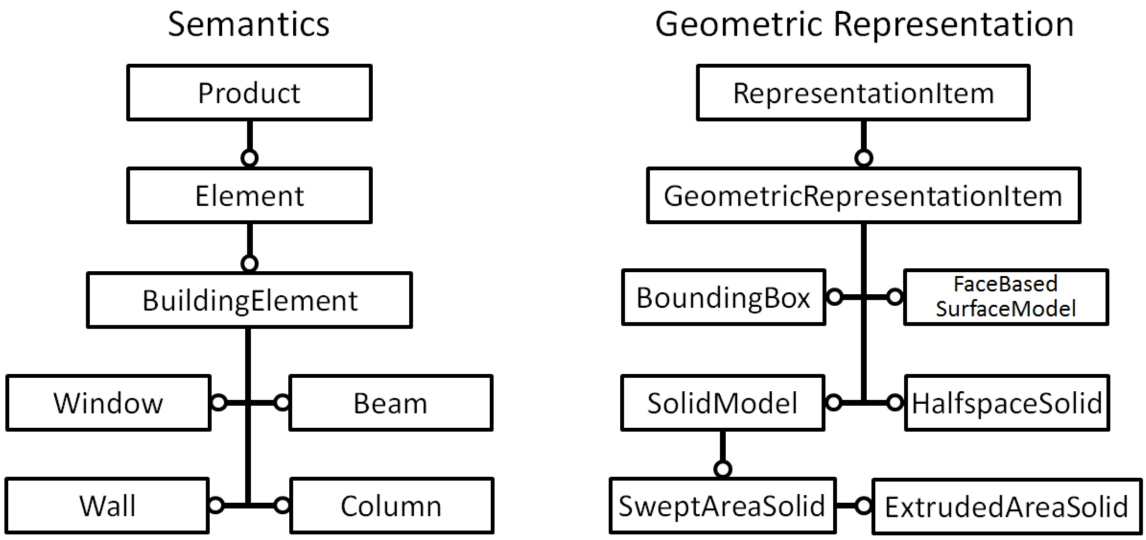


Fig. 1: Separation of semantics and geometric representation in the IFC (EXPRESS-G diagram)

The root object of an IFC model is an instance of *IfcProject*. Starting from this object, multiple *IfcRelAggregate* relationship instances are successively employed to create an aggregation hierarchy comprising the site, the building(s), the building part(s) and the building storey(s). The corresponding classes are sub-classes of *IfcSpatialStructureElement*. The actual building elements (wall, columns, etc.) are subsequently associated with one or more stories by means of the relationship *IfcRelContainedInSpatialStructure* (Fig. 2).

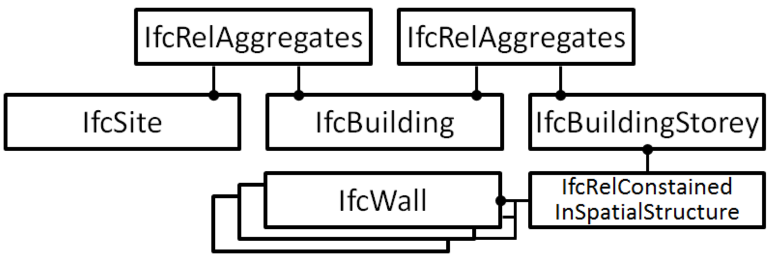


Fig. 2: The spatial aggregation hierarchy provided by the semantic parts of the IFC (EXPRESS-G diagram)

In addition, space objects can be included in the model to represents rooms. They should be associated with the surrounding walls by means of the *IfcRelSpaceBoundary* relationship. Each semantic object representing a building element or a space can be associated with one or more geometric representations. This is realized by associating the *IfcProduct* instance with an *IfcProductRepresentation* instance which in turn may refer to a number of instances of *IfcRepresentation* (Fig. 3). Possible options for representing geometry in IFC are Boundary Representation, Constructive Solid Geometry, and Swept Solid, among others.

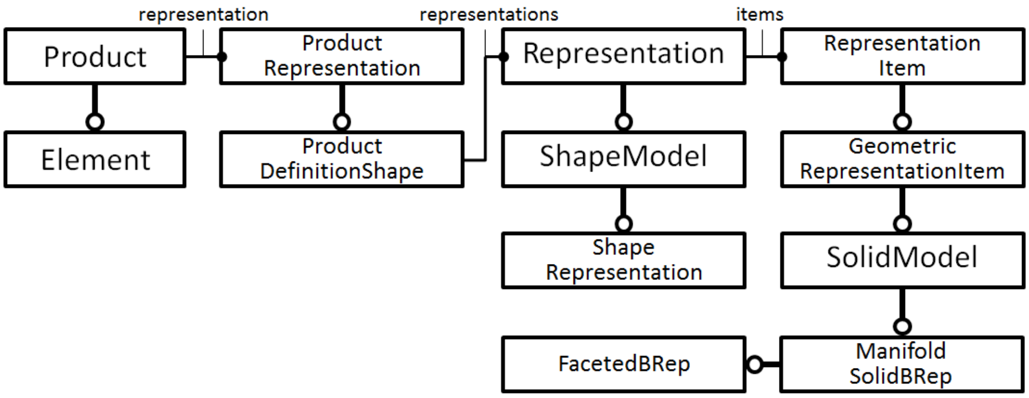
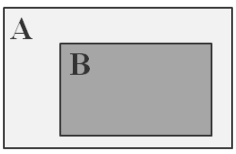


Fig. 3: Association of a semantic object with geometric representations (EXPRESS-G diagram)

If the IFC model is exported correctly by the BIM authoring application, the aforementioned relationships are set such that they comply with the geometric representation. For example, a building element and a space are associated via the *IfcRelContainedInSpatialStructure* relationship, if, and only if, the corresponding geometric objects do fulfill the containment relationship. However, due to the sheer complexity of the IFC model, in many cases erroneous models are created. While geometry is often handled correctly, particularly critical is the accurate use of the relationships with spatial semantics. It is here where inconsistencies between the geometric and semantic representation can easily arise. In the next section we present an approach for checking the consistency by means of a query language.

4. QL4BIM – A QUERY LANGUAGE FOR BUILDING INFORMATION MODELS

To realize the checking functionality described above, the Query Language for Building Information Models (QL4BIM) presented in (Borrmann & Rank, 2009a, 2009b, Daum & Borrmann 2013a, 2013b) is utilized. On the one hand, the query language provides an object-oriented access to the IFC model (Daum & Borrmann, 2013b). The main feature, however, is its strong support for temporal and spatial operators which allows users to operate on a more abstract level and formulate high-level queries such as "Select all walls located above slab 1 but constructed earlier". The spatial operators comprise metric, directional and topological operators (Borrmann & Rank, 2009a, 2009b). The topological operators – which are of particular interest here – make it possible to analyse topological relationships between objects in three-dimensional space. The defined predicates correlate two spatial entities and can be described by the 9-Intersection Model (9-IM) introduced in (Egenhofer, 1991). The 9-IM calculus is based on the mathematical theory of Point Set Topology (Gaal, 1964) which applies the notion of the neighbourhood of a point to describe topological concepts such as the interior $A°$, the boundary δA and the exterior A^{-} of a point set A.



$$I = \begin{pmatrix} A° \cap B° & A° \cap \partial B & A° \cap B^{-} \\ \partial A \cap B° & \partial A \cap \partial B & \partial A \cap B^{-} \\ A^{-} \cap B° & A^{-} \cap \partial B & A^{-} \cap B^{-} \end{pmatrix} = \begin{pmatrix} \neg\emptyset & \neg\emptyset & \neg\emptyset \\ \emptyset & \emptyset & \neg\emptyset \\ \emptyset & \emptyset & \neg\emptyset \end{pmatrix}$$

A contains B

Fig. 4: Contain relationship described by the 9-Intersection Model

The intersections of interior, boundary and exterior of two entities result in a 3×3 matrix. The individual entries indicate if there is an empty or a non-empty set for the particular intersection. Fig. 4 shows the 9-IM matrix for a simplified 2D constellation where object A is *inside* object B and object B *contains* object A, respectively.

The 9-IM matrix can be used to define the topological predicates *Disjoint, Equal, Touching, Containing, Inside-of, Overlapping, Covering* and *Covered-by* in 3D space as depicted in Fig. 5. The algorithms developed to implement the topological operators populate a 9-IM matrix by performing tests on the operands' geometry. Two different approaches have been developed: one operating on an octree representation (Daum & Borrmann, 2012) and another operating on the boundary representation (Daum & Borrmann, 2013a).

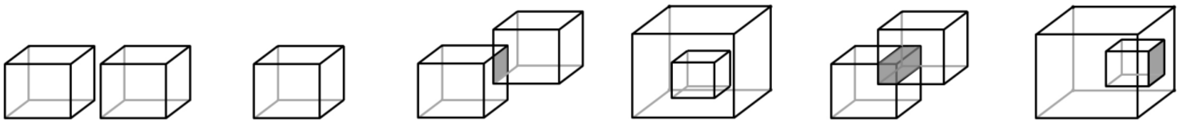


Fig. 5: Available topological predicates provided by the query language (Borrmann & Rank, 2009b)

QL4BIM make use of the LINQ technology as it provides powerful query mechanisms for in-memory collections and object networks. LINQ is neatly integrated into the .NET framework and queries can be formulized in C# syntax. The queries are type safe and attributes and methods of involved objects can be used. For the definition of a query, an anonymous function, called a Lambda expression is defined. QL4BIM acts directly on the IFC object model and is thus well suited for queries with semantic subparts. For more information concerning the query system, see (Daum & Borrmann, 2013b).

5. CHECKING THE SPATIO-SEMANTIC CONSISTENCY OF IFC MODELS USING QL4BIM

In this contribution we present a concept for the validation of spatio-semantic consistency of IFC models using QL4BIM. The spatial structure described in the semantic part is validated by means of the available geometry representations. Spatio-semantic inconsistencies typically arise as a product of modeling mistakes by the user. Additionally, the complexity of the IFC model contributes to the erroneous import or export functionality of the BIM authoring application, which may also result in corrupted building models.

The developed approach comprises two parts: first, the model's spatial hierarchy built up by *IfcSite*, *IfcBuilding*, *IfcBuildingStorey* and *IfcSpace* entities is inspected; and second, the topological relationships between *IfcProducts* with their superior spatial structure, e.g. an *IfcBuildingStorey*, are evaluated.

5.1 Spatio-semantic consistency of the IfcRelAggregates relationship

In the first part of processing, the entities that define the spatial structure are fetched from the IFC model. In a plain configuration, a hierarchical structure similar to Fig. 6 should be found. When iterating over all *IfcRelAggregates* relationships, *IfcsSites* and related entities are topologically examined. The geometric representation of *IfcSite* and *IfcBuilding* are described by *IfcProductDefinitionShape* and *IfcLocalPlacement* objects. As a general concept of the IFC, it is possible to associate several geometry representations with one entity if this is required in a particular context.

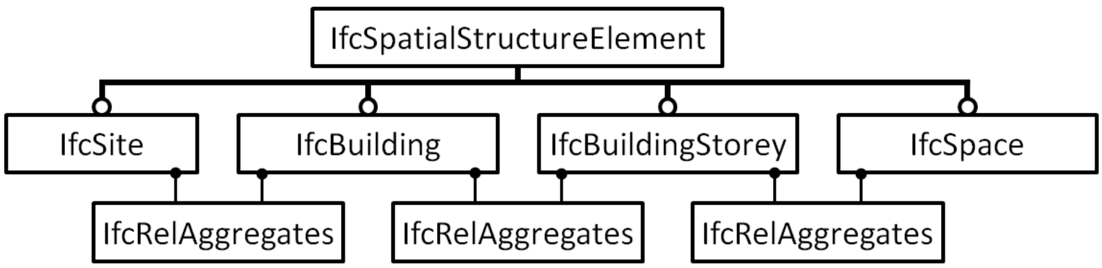


Fig. 6: Exemplary IFC spatial structure established by IfcRelAggregates relationships (EXPRESS-G diagram)

In the developed prototype system for all instances of *IfcProduct* an explicit geometry representation is generated and made available as *IfcFacetedBrep* via the Shape attribute of the *IfcProduct* object. The complete query formulated in QL4BIM is shown in Fig. 7. It returns all non-conforming *IfcBuilding* objects combined with their hosting *IfcSite* for further manual review.

```
IfcRelAggregates.Select(a =>                //simplified version without handling of
                                            //unsupported types
{
    var site = a.RelatingObject As IfcSite;
    var shapeSite = site.Shape;
    var nonconfirmingBuildings = new List<IfcBuilding>();

    foreach relatedObject in a.RelatedObjects
    {
        var building = relatedObject As IfcBuilding;
        var shapeBuilding = building.Shape;

        var allowed =   shapeSite.Contain(shapeBuilding) ||
                        shapeSite.CoveredBy(shapeBuilding);
        if(!allowed)
            nonconfirmingBuildings.Add(building);
    }
    return new Tuple<IfcSite, List<IfcBuilding>>(site, nonconfirmingBuildings);
}
```

Fig. 7: Query returning IfcSite objects and related, topological non-conforming IfcBuilding objects

In QL4BIM all objects from a given set, e.g. *IfcRelAggregates*, are examined in the query expression. In the developed algorithm, the types of the related and relating objects are first checked. For reasons of clarity, this is not shown in the depictured code in Fig. 7. If the appropriate types are present (e.g. an *IfcSite* and *IfcBuildings*), topological processing is executed by calling the *Containing* and *Covered-by* predicates.

These are the topological allowable attributes of aggregated *IfcSite* and *IfcBuilding* objects as demonstrated in Fig. 8. Buildings that do not conform to these topological predicates indicate that there is an error in either the topological definition or in the used geometry representations. Therefore, a list of buildings is linked with each site and erroneous buildings are added. Finally, the query yields an enumeration of all tuples, each containing one site object and its topologically non-confirming building objects.

The same approach can be applied for checking the spatio-semantic consistency of the remaining aggregation relationships, e.g. *IfcBuilding* objects related to *IfcBuildingsStorey* objects and *IfcStorey* objects related to *IfcSpace* objects. Here, the type selection has to be adapted accordingly.

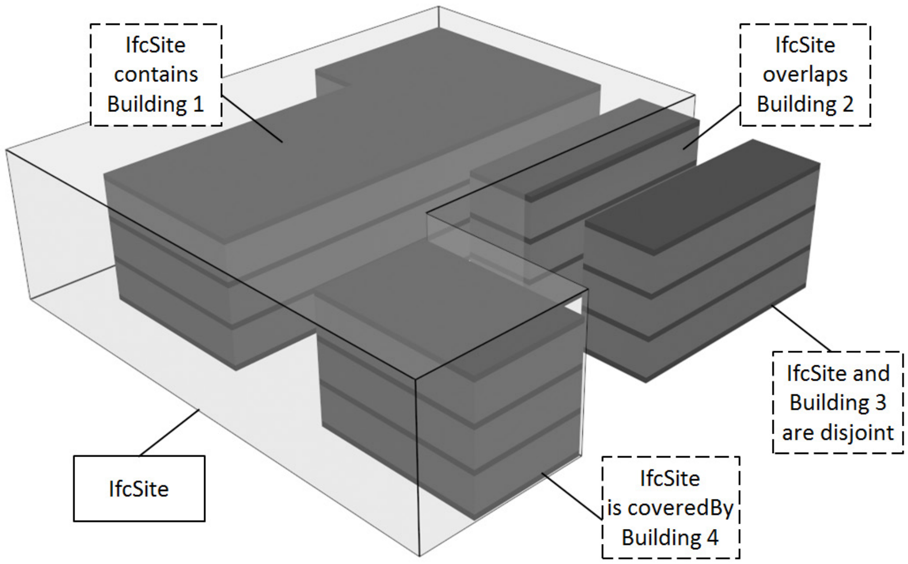


Fig. 8: The geometry representation of an IfcSite and the topological classification of its IfcBuilding objects

Additionally, the IFC model makes it possible to group entities used in the project's spatial structure. As an example, an *IfcBuildingStorey* object can be associated with its child storeys. In this case, the parent storey reflects its grouping semantic by a *CompositionType* attribute of the value *COMPLEX*. In the nested children this attribute is set to *PARTIAL* as shown in Fig. 9. The *CompositionType* member variable is available in all subtypes of *IfcSpatialStructureElement*. If such nesting relationships are present in the model, the spatio-semantic consistency can also be verified using the same processing method except that only one type is involved in the query, e.g. *IfcBuildingStorey* or *IfcSpace*.

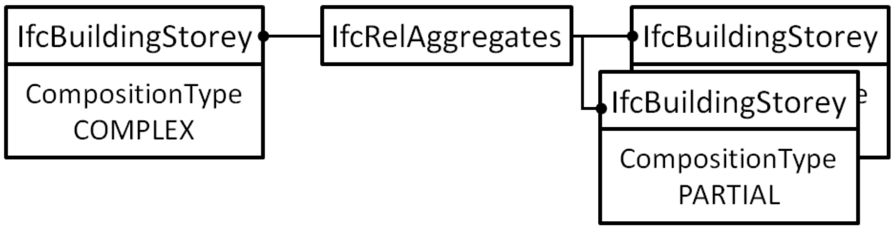


Fig. 9: Example of a grouping established by nested IfcSpatialStructureElement objects (EXPRESS-G diagram)

5.2 Spatio-semantic consistency of the IfcRelContainedInSpatialStructure relationship

As described above, it is possible to establish a spatial structure semantically by relating *IfcSpatial-StructureElements* like *IfcSite*, *IfcBuilding* and *IfcBuildingStorey*. Furthermore, the IFC model is able to reflect a containment relationship of products and a superior *IfcSpatialStructureElement*. This important semantic information is used frequently in downstream processes like resource management and construction scheduling. For example, equally leveled columns are connected to the storey they are on. This is realized using the *IfcRelContainedInSpatialStructure* relationship. An *IfcElement*, subtype of *IfcProduct*, can only be assigned once to one *IfcSpatialStructureElement*. Typically, the Brep geometry of the spatial structure contains the element's geometry. On rare occasions, the contained element overlaps the spatial structure to which it is related. As an example, a lift shaft might be modeled as contained by the ground level storey. The other storeys connect to the shaft via *IfcRelAggregates* objects. This means that elements with geometry representations that do overlap *IfcSpatialStructureElements* cannot be generally declared as false. The decision as to how to handle overlapping situations must be made on project level. The exemplary query for the verification of containment relationships of *IfcElements* and *IfcSpatialStructureElements* is shown in Fig. 10.

```
IfcRelContainedInSpatialStructures.Select(a =>
{
    var spatialStructure = a.RelatingObject As IfcSpatialStructureElement;
    var spatialStructureShape = spatialStructure.Shape;
    var nonconfirmingElements = new List<IfcElement>();

    foreach relatedObject in a.RelatedObjects
    {
        var element =   relatedObject As IfcElement;
        var elementShape = element.Shape;

        var allowed =   spatialStructureShape.Contain(elementShape) ||
                        spatialStructureShape.CoveredBy(elementShape) ||
                        spatialStructureShape.Overlap(elementShape);

        if(!allowed)
            nonconfirmingElements.Add(element);
    }
    return new Tuple<IfcSpatialStructureElement, List<IfcElement>>
                    (spatialStructure, nonconfirmingElements);
}
```

Fig. 10: Query returning IfcSpatialStructureElement objects and associated non-conforming IfcElement objects

For each *IfcRelContainedInSpatialStructure*, its related object of type *IfcSpatialStructureElement* is fetched to receive the referenced Brep geometry. The return type is an enumeration of tuples in which the first element is a spatial structure. The tuple's second element represents a list of *IfcElement* objects. The query thereby yields *IfcSpatialStructureElements* that are connected to topologically defective *IfcElements*. The returned tuples then have to be revised and the user needs to determine whether the failure arises due to errors in the defined geometry representations or topological deficits in the building information model.

6. EXAMPLE

In the following, we consider the scenario of a structural model of an office building. A 3D view of the building is depictured in Fig. 11.

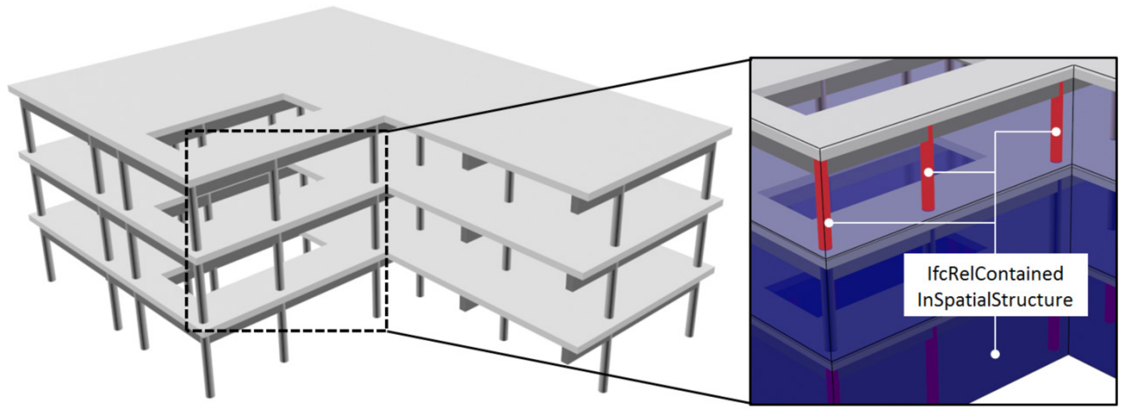


Fig. 11: Structural model of an office building with topologically erroneous containment relations

For the end user, the scene seems to be accurate because defects in the topological definitions of the model cannot be recognized without undertaking a formal validation. This checks the geometry information available in the model against the topological relationships. As shown on the right side of Fig. 11, three columns of the second storey are erroneous related to the ground level's spatial structure, an *IfcBuildingStorey*.

In the IFC model, the error is encoded in the XML markup in the *IfcRelContainedInSpatialStructure* elements concerning the three columns. For the first column with id=i34066 this XML element is shown in Fig. 12. In the *RelatingStructure* element, an incorrect reference to the *IfcBuildingStorey* id=i1595 is established. This leads to a configuration in which the column is modeled as spatially contained by the ground level storey.

```
<IfcRelContainedInSpatialStructure id="i34102">
        <GlobalId>35r2O_4kTAf8AbY</GlobalId>
        <RelatedElements exp:cType="set">
                <IfcColumn ref="i34066"/>
        </RelatedElements>
        <RelatingStructure>
                <IfcBuildingStorey ref="i1595"/>
        </RelatingStructure>
</IfcRelContainedInSpatialStructure>
```

```
<IfcBuildingStorey id="i1595">
        <GlobalId>0hozoFnxj9leO</GlobalId>
        <Name>01 - Entry Level</Name>
        <ObjectPlacement>
                <IfcLocalPlacement ref="i1594"/>
        </ObjectPlacement>
        <LongName>01 - Entry Level</LongName>
        <CompositionType>element</CompositionType>
        <Elevation>0.</Elevation>
</IfcBuildingStorey>
```

Fig. 12: ifcXML encoding of an erroneously established containment relationship

This kind of error can arise as a result of a mistake in the editing of the model or as a product of an inaccurate export of the IFC data. Although not recognizable in the visualization, such undetected mistakes in the modeling of a building can cause problems in the downstream process. High quality results and efficient workflow in the construction phase can only be achieved if the data basis is accurate. For example, difficulties concerning material deliveries are expected to occur here. When the ground level is constructed, material for the three erroneously included columns is stored but not used. This material must be stored until it is actually needed, which is not before the third storey is built. If such errors accumulate, the construction of a building becomes more difficult and the time required and financial expenditure increases. If the query defined in Fig. 10 is used to examine all *IfcRelContainedInSpatialStructure* objects in the IFC model, it will return a tuple containing the *IfcBuildingStorey* i1595 and a list containing the three problematic *IfcColumns*.

7. CONCLUSION AND FUTURE WORK

This contribution presented a new approach for the computational validation of spatio-semantic consistency of IFC-based building information models using the query language QL4BIM. As a key aspect, the query language provides access to the semantic model of the IFC and at the same time makes it possible to apply high-level spatial operators that act directly on the geometric representations of the individual objects. Combining these features makes it possible to efficiently and flexibly formulate rules for validating spatio-semantic consistency.

The presented examples show that deficits in the established spatial structure of components and virtual containers can be reliably detected. The methods developed enable the end user of building information models to inspect even large data sets efficiently. This significantly contributes to improving the quality of IFC models. Finally, this enhances efficient workflows and cost-effectiveness in the buildings' construction phase.

In future research, we will integrate semi-automatic repair functionality into the system that automatically produces proposals for expert users to help them create the correct spatial structure of building elements and spaces.

8. REFERENCES

Borrmann, A., and Rank, E. (2009a). Specification and implementation of directional operators in a 3D spatial query language for building information models, *Advanced Engineering Informatics* AEI 23 (1), pp. 32-44. 2009.

Borrmann, A., and Rank, E. (2009b). Topological analysis of 3D building models using a spatial query language, *Advanced Engineering Informatics* AEI 23(4), 370-385.

bimtaskgroup (2013), UK Government BIM Strategy, http://www.bimtaskgroup.org/ (10. May 2013).

buildingSMART Ltd. (2013). IFC data schemas, Industry Foundation Classes http://www.buildingsmart-tech.org/ifc/IFC2x3/TC1/html/index.htm (10. May 2013).

Daum, S., and Borrmann, A. (2013a). Boundary Representation-Based Implementation of Spatial BIM Queries, *Proceedings of the 20th EG-ICE International Workshop* (EG-ICE 2013).

Daum, S., and Borrmann, A. (2013b). Definition and Implementation of Temporal Operators for a 4D Query Language, *Proc. of the ASCE International Workshop on Computing in Civil Engineering* (ASCE IWCCE 2013).

Daum, S., and Borrmann, A. (2012). Efficient and Robust Octree Generation for Implementing Topological Queries for Building Information Models, *Proc. of the 19th EG-ICE International Workshop* (EG-ICE 2012).

Eastman, C. M., et al. (2011): BIM handbook. A guide to building information modeling for owners, managers, designers, engineers and contractors. 2nd Edition, Hoboken, NJ,Wiley.

Egenhofer, M. and Herring, J. (1989). A mathematical framework for the definition of topological relationships, *Proceeding. of the 4th Int. Symp. on Spatial Data Handling.*

Gaal, S. A. (1964). Point set topology (Vol. 16). Academic Press.

Mazairac, W., and Beetz, J. (2013). BIMQL - An Open Query Language for Building Information Models, *Advanced Engineering Informatics*, accepted.

NBIMS-US, US National BIM standard (2013). http://www.nationalbimstandard.org/ (10. May 2013).

SCRA (2006), STEP Application Handbook, ISO 10303, Version 3, http://www.uspro.org/ (10. May 2013).

Stadler, A., and Kolbe, T. H. (2007). Spatio-semantic Coherence in the Integration of 3D City Models. *Proceedings of the 5th International Symposium on Spatial Data Quality,* Enschede.

MAPPING BETWEEN BIM MODELS AND 3D GIS CITY MODELS OF DIFFERENT LEVELS OF DETAIL

Jack Cheng, Yichuan Deng & Qianru Du
The Hong Kong University of Science and Technology

ABSTRACT: *Modeling the built environment of a city digitally in three dimensions can support navigation, urban planning, disaster management, and energy consumption analysis. City Geography Markup Language (CityGML) was developed in recent years as a Geographic Information System (GIS) data standard to represent the geometry and geographical information of buildings in digital 3D city models. CityGML supports modeling on various Levels of Detail (LoDs) from simple box models to models with interior partitions. This paper presents the theoretical framework that we have developed for mapping between Building Information Modeling (BIM) models in the Industry Foundation Classes (IFC) format and CityGML models of different LoDs. The framework consists of two major parts – (1) transformation between BIM models and high level CityGML LoD4 models, and (2) harmonization among the four LoDs of CityGML. For the first part, a reference ontology was developed to transfer semantic information between BIM models in the IFC format and CityGML models. To reduce the file size of the generated CityGML models, a new geometric transformation algorithm was developed for the mapping from Swept Solid or Constructive Solid Geometry (CSG) representations, which are commonly used in BIM models, to Boundary Representation (BRep) which is used in CityGML models. For the second part, schema mediation techniques are used to convert CityGML models from one LoD to another LoD. Based on the reference ontology, an application domain extension (ADE) called "Semantic City Model (SCM)" was developed for CityGML. The SCM ADE enriches CityGML models by providing more semantic information such as the linkage relationship between walls and building stories. This paper presents the developed mapping framework with an illustrative example of a residential building.*

KEYWORDS: *3D city models, Building Information Modeling (BIM), Geographic Information System (GIS), Industry Foundation Classes (IFC), Schema mapping*

1. INTRODUCTION

Modeling city objects in 3D environments can improve the capabilities of Geographic Information Systems (GIS). The traditional 2D GIS does not support applications that require the data of object height or elevation, such as indoor ventilation modeling or indoor navigation. By 3D modeling the GIS can provide analysis results on the scale of "rooms" or "spaces" rather than "districts" or building blocks. Moreover, some simulations performed on GIS also require the 3D details of building interior. For example, Strzalka et al. (2011) showed an urban scale heating energy demand forecasting system based on 3D GIS models. Given the demand for those indoor 3D data of buildings, however, the acquisition of such data is hard due to the fact that there are many hidden components in the building which are not able to be discovered by traditional ways such as laser scanning. In this sense, 3D models from Building Information Modeling (BIM) can serve as data source for constructing 3D GIS city models.

BIM is the process to create, store and manage relevant data of a building throughout its whole lifecycle (Eastman et al., 2008). BIM models are data rich models which not only represent the geometry of building components, but also assign attributes to them. Semantic information such as owner, construction time and cost is available from BIM models. As an emerging technology in the Architecture, Engineering and Construction (AEC) domain, BIM is now getting wider and wider adoptions. This provides the possibility and availability of BIM models as the data source for GIS. Besides providing 3D building geometry information, BIM can extend the data richness of GIS models by providing semantic information of building components.

Feeding information of BIM to GIS models involves the process of automatic transformation of BIM data into GIS data, including schema harmonization and data mapping between BIM and GIS data standards. There have been a number of studies concerning this topic. El-Mekawy et al. (2011) proposed an ontology called the Unified Building Model (UBM) to merge Industry Foundation Classes (IFC) and City Geography Markup Language

Citation: Cheng, J., Deng, Y. & Du, Q. (2013). Mapping between BIM models and 3D GIS city models of different levels of detail. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

(CityGML), which are representative data standards in the BIM and GIS domains, respectively. Herrlich et al. (2010) described a mapping between IFC and Collada for geographic data visualization in gaming environment. Hijazi et al. (2011) tried to write the utility information in IFC into CityGML using CityGML–UtilityNetwork ADE. In their BIM Server platform, van Berlo and de Laat (2011) also showed a mapping between IFC and CityGML, in which they tried to write the geometry of BIM models into CityGML models. All these works show the potential of mapping BIM with GIS models, and indicate that BIM models are far more detailed than the traditional GIS models. However, no complete mapping between BIM models and building objects in 3D GIS model has been reported so far. For example, in (van Berlo and de Laat, 2011), some building components are missing after transformation to GIS model. Also, the mapping of semantic information from BIM to GIS is still lacking, which is a great waste of the information in BIM models.

This paper tries to address this issue by proposing a mapping framework which can achieve a complete data transformation from BIM models to GIS models. IFC and CityGML are chosen as demonstrating data schemas for BIM and GIS because of their wide applications in these two domains. The mapping framework involves the harmonization between IFC and CityGML, and data mapping and extension development for GIS models in order to store the semantic information from BIM models. Furthermore, as extension to this work, in order to widen the application areas of the generated GIS models, the issue of harmonization between different Levels of Detail (LoD) in CityGML is also discussed and demonstrated.

The remainder of this paper is structured as follows: Section 2 provides some background information about IFC, CityGML and LoDs in CityGML. Critical issues in the mapping are also discussed. Section 3 addresses these issues and presents the development of the CityGML Application Domain Extension (ADE) that we proposed for BIM models, namely the Semantic City Model (SCM). Section 4 explains the details of harmonization between LoDs in CityGML. The proposed framework and the LoD harmonization process is demonstrated and discussed in Section 5. Finally, conclusions are made in Section 6.

2. BACKGROUND

IFC is an EXPRESS-based open data standard initiated by buildingSMART. Supported by most of the common BIM software in the AEC industry, IFC is believed to be the most popular BIM standard. On the other hand, CityGML is a newly accepted GIS standard developed by Special Interest Group 3D (SIG 3D) of the initiative Geodata Infrastructure North-Rhine Westphalia (GDI NRW) in Germany. It was adopted as an official OGC (Open Geospatial Consortium) standard in 2008 by OGC members. It is a semantic-rich data standard which supports five Levels of Detail (multi-resolution) modeling of city objects. In order to deal with special applications in 3D city models, CityGML also allows users to create extensions to the schema, namely the ADE (Kolbe, 2009).

IFC and CityGML are now widely used in the AEC domain and the GIS domain, respectively. Serving as interim data standards, they can facilitate the information exchange process inside the domain (Lipman, 2009, Döllner et al., 2006). However, the gap of data exchange between these two data standard has never been fulfilled. IFC and CityGML are serving different purposes. IFC intends to capture every detail concerning the building whereas CityGML focuses more on the geometry of city objects. Although a complete transformation of geometry information in IFC to CityGML is possible, most of the semantic information in IFC will be lost due to the narrow definition of semantic information in CityGML. Moreover, the transformation of geometry information from IFC to CityGML is also challenging. IFC usually employs a local coordinate system while CityGML uses a universal world coordinate system. Objects in IFC are represented by one of or the combination of Boundary Representation (BRep), Constructive Solid Geometry (CSG) and Swept Solid while CityGML only utilizes the BRep to represent objects. In order to reach a complete data transformation, the transformation from local placement coordinate systems to world coordinate system, from CSG or Swept Solid to BRep must be realized, which is supported by an efficient parser that is able to capture all the information from IFC. To avoid loss of semantic information, ADE must be developed for CityGML. These issues will be addressed in Section 3.

CityGML supports representation of city objects in five LoDs in order to satisfy needs for different applications. For example, Strzalka et al. (2011) reported a heat demand forecast system based on the CityGML LoD 1 model. In their conclusions, they stated that a LoD 2 city model would result a higher accuracy. Although there are detailed definitions about LoDs in CityGML, OGC does not specify the transformation method between LoDs. Fan and Meng (2009) tried to address this issue by developing an automatic translator between LoDs. However, in their LoD 3 to LoD 2 method, the referred methodology in (Fan et al., 2009) was not applicable for building with complex envelope. Also the proposed framework in their paper is no longer valid for the newer version of

CityGML. In Section 4 of this paper, we will propose new transformation methods for LoD 3 to LoD 2 and present an automatic transformation between all LoDs.

3. FRAMEWORK FOR TRANSFORMATION FROM IFC TO CITYGML

3.1. Overview

IFC employs the EXPRESS data modeling language to represent building objects, in which all the relationships between objects such as "contained in" or "structural member of" are clearly defined. These relationships are called "inverse attributes" in IFC schema. Inverse attributes are important for developing the parser for IFC. For example, getting the "contained in" attributes of a building will result in getting all the components belonging to the building. Inverse attributes are also important attributes for building objects. van Berlo and de Laat (2011) proposed an ADE called GeoBIM for CityGML in which they defined some semantic information from IFC for CityGML. However, they did not considered the inverse relationships in the ADE and thus losing a lot of information about relationships of objects from BIM models. El-Mekawy et al. (2011) developed a Unified Building Model to mapping BIM with CityGML. But inverse attributes were not considered either. Our framework starts with developing the parser for IFC and CityGML using inverse attributes. Then the transformation of local coordinate system and CSG/Swept Solid is used in the data processing stage. CityGML models with semantic information are generated using the proposed ADE called Semantic City Model (SCM).

3.2. Parser Strategy

The root entity of IFC files is usually the IfcProject entity, linked by inverse attributes to entities such as IfcBuilding or IfcSite. IfcBuilding will then be linked to IfcBuildingStorey, and so on and so forth. This immediately indicates two possibilities of developing the parser: Top-down approach and Bottom-up approach. The Top-down approach takes the root of the IFC file first and finds its child entities while the Bottom-up approach searches for the indivisible objects and starts building the tree from these leaves. The Bottom-up approach is efficient for BIM models with small amount of components as it neglects some unnecessary searches. However, for complex building models, the reconstruction time of the whole file tree may be too long due to the fact that more than one relationship may exist between objects. So the parser strategy adopted in our framework is the Top-down approach. The parser will find IfcProject and the related IfcBuilding by looking at these inverse-attributes, and then continue to go down until all the building components are visited. The process is illustrated by Fig. 1, taking transformation of wall components as an example. The solid lines show the parsing route and the dashed lines show the information flow.

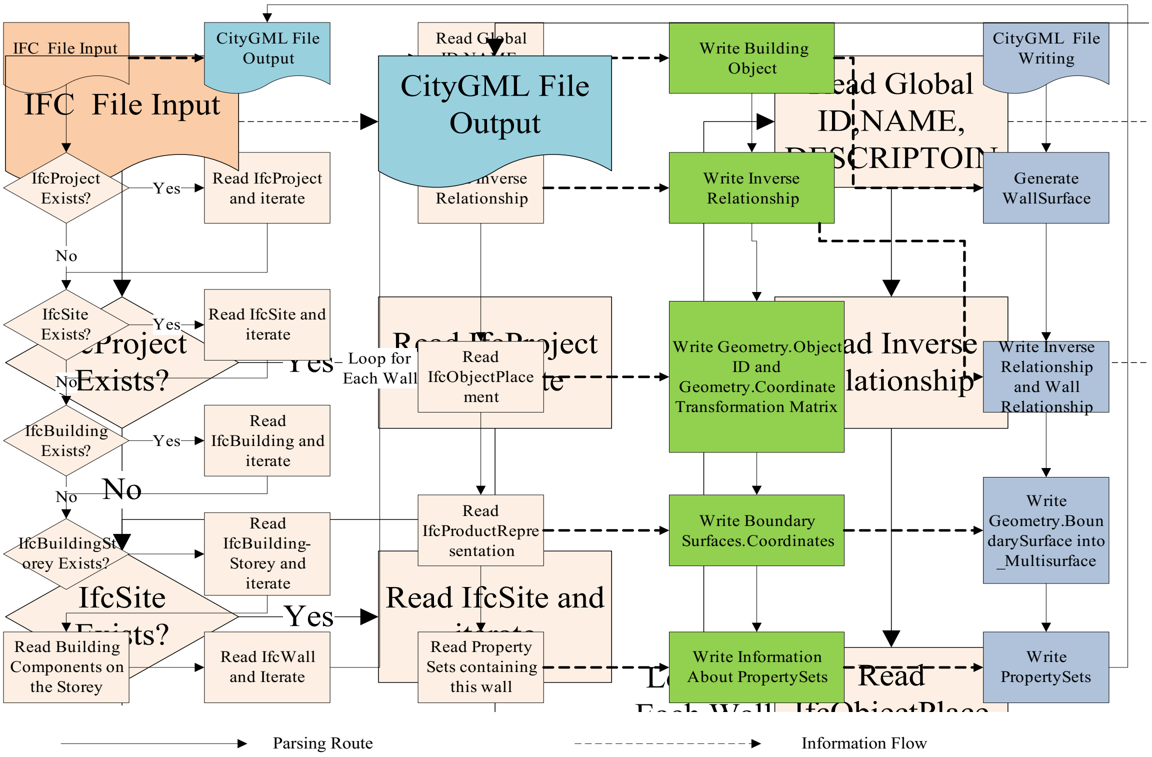


Fig. 1: Overview of data mapping process

3.3. Data processing: Transformation of local placement system and CSG/Swept Solid

IFC uses a local coordinate placement system to determine the position of objects. Despite the convenience it will bring while copying entity information, the local placement system will cause trouble for the mapping from IFC to CityGML. In order to transform the local placement system to world coordinate system, every IfcAxis2Placement3D entity will be transformed into a 4x4 transformation matrix M. Multiplying the points to the series of transformation matrix will result in the point location in world coordinate system. Fig. 2 illustrates the process of producing transformation matrix from IfcAxis2Placement3D.

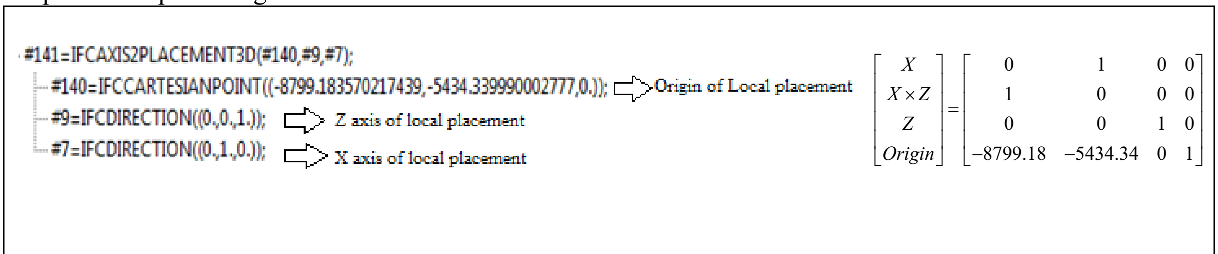
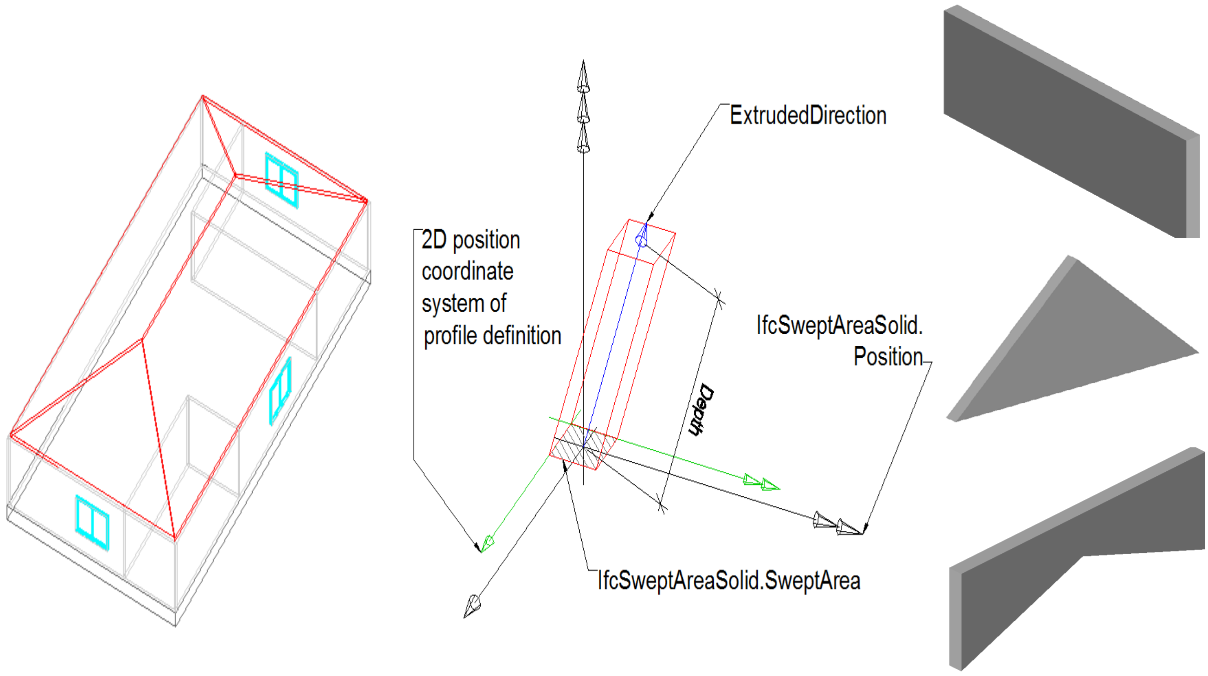


Fig. 2: Generating Transformation Matrix

In IFC models, most of the solid building components are represented by CSG or Swept Solid. The differences between BRep, Swept Solid and CSG are shown in Fig. 3. In the proposed framework, all these solid models will be broken into surfaces that represent the exterior of the object. The coordinates of the surfaces are then transformed into world coordinate system and written into CityGML.



Boundary Representation

Swept Solid (Adopted from IFC 2x3 documentation)

CSG

Fig. 3: BRep, Swept Solid and CSG

3.4. Data mapping for semantic information

Most semantic information found in IFC files, such as owner history, cost, construction time and inverse attributes, could not find the corresponding entity in CityGML files. The only solution to keep the semantic information is to extend the schema of CityGML. The ADE function in CityGML allows user to create application-specific data schemas based on the original data schema of CityGML. The Semantic City Model ADE for CityGML is the result of this approach, in which the semantic information in BIM models is mapped to ADE entities.

There are two major groups of semantic information in IFC, which are inverse attributes defining the relationships and property sets that contain information directly related to the object. These two groups form the two children of the ADE root. In the inverse attributes, some common attributes are extracted and others are specified according to the type of component. Fig. 4 shows an example of the ADE which is created specifically for the wall surfaces in CityGML.

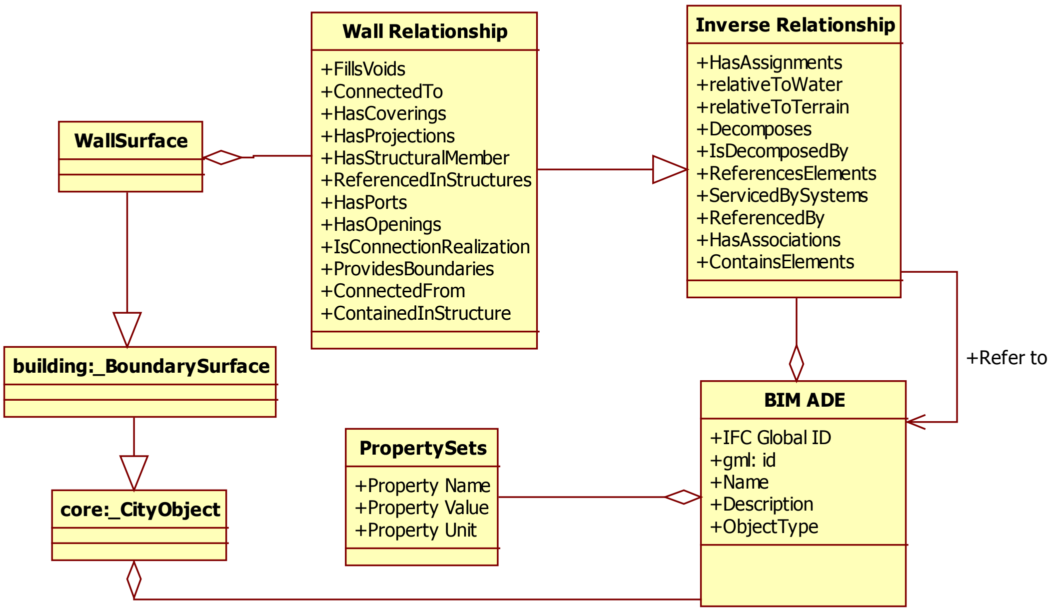


Fig. 4: CityGML SCM ADE for *bldg:WallSurface*

4. HARMONIZATION BETWEEN LODS IN CITYGML

4.1. Overview

CityGML supports five Levels of Detail (LoDs) in order to provide the possibility of representing objects in different resolution. Aiming at the needs for various applications such as visualization or simulation, the five LoDs are able to provide different options for users. Different LoDs could exist simultaneously in the same model and models with different LoDs are also able to work and integrate with each other (Kolbe et al., 2005). In the harmonization process, we will firstly give a strict definition to each LoDs, and then an automatic transformation process is proposed and tested.

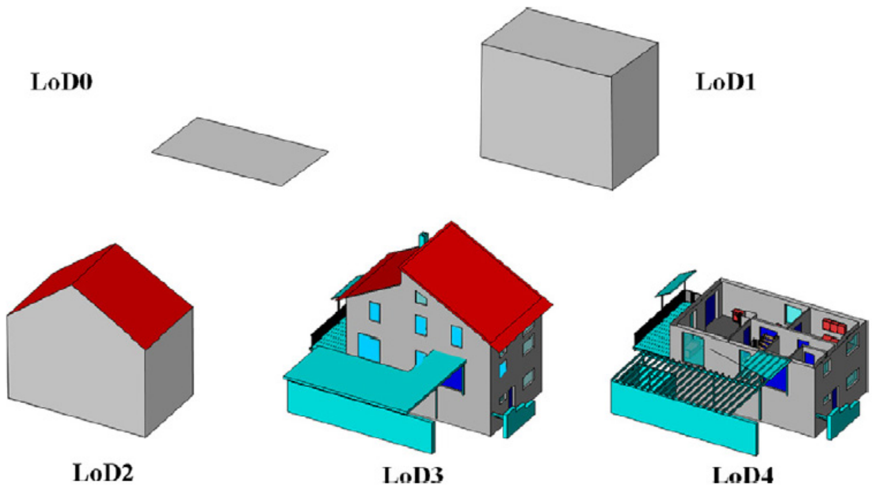


Fig. 5: LoDs in CityGML (Adopted from (Gröger and Plümer, 2012))

4.2. Definitions of each LoD

According to (Gröger et al., 2012), the LoD 0 model is simply the 2.5 dimensional Digital Terrain Model, which is a two dimensional map with 3D terrain. The LoD 1 to LoD 4 models are 3D models that are able to represent 3D buildings. LoD 1 is the well-known blocks model while LoD 2 models add roof structures and textures to the LoD 1 model. The LoD 3 models provide the details of external walls, roof, balconies and bays. Finally, the LoD

4 model completes a LoD 3 model by adding interior building components such as rooms and furniture. Fig. 5 shows an overview of LoDs.

Until now OGC does not give a strict definition of LoDs in CityGML, so users could generate models based on their own understanding about the LoDs. However, this flexibility can also be seen as a drawback as there are no rules about whether certain objects should exist in a specific LoD model or not (Gröger and Plümer, 2012). The first step of the harmonization would be defining each LoD in detail. As we are dealing with 3D building models, only LoD 1-4 is considered.

It is not easy to give a strict definition for each LoD as the scope of source references is narrow. We analyze the definitions of LoDs based on the following sources:

A. CityGML specifications and encoding standard from OGC, such as (Gröger et al., 2008, Gröger et al., 2012).

B. Data sets recommended by the official CityGML website. By analyzing different LoDs, whether one entity exists in certain LoD can be determined. If conflict occurs, we refer to first source.

C. Papers about CityGML and Levels of Detail in 3D GIS models, such as (Fan and Meng, 2009, Gröger and Plümer, 2012, Döllner and Buchholz, 2005).

All the sources were analyzed and a cross-reference work was done to check whether there are conflicts. The final definition for each LoDs in terms of existence of entities is shown in Table.

After acquiring the definitions of each LoD, the automated transformation between LoDs is performed on Java platform using CityGML4j and JAXB.

Table 1: Definitions of LoDs in CityGML

Attributes	**LoD1**	**LoD2**	**LoD3**	**LoD4**
Room	×	×	×	√
_Opening —Window —Doors	×	×	√	√
IntBuildingInstallation	×	×	×	√
BuildingFurniture	×	×	×	√
Ceiling Surface	×	×	×	√
Interior Wall Surface	×	×	×	√
Floor Surface	×	×	√	√
Roof Surface	×	√	√	√
BuildingInstallation	×	√	√	√
Wall Surface	×	√	√	√
Ground Surface	×	√	√	√
Closure Surface	×	√	√	√
OuterCeilingSurface	×	√	√	√
OuterFloorSurface	×	√	√	√
Geometry(GML)	×	√	√	√
Solid(GML)	√	√	√	√
Mutisurface(GML) — FootPrint/RoofEdge	√	√	√	√
Absolute 3D point accuracy	5/5m	2/2m	0.5/0.5m	0.2/0.2m

Attributes	LoD1	LoD2	LoD3	LoD4
(position / height)				
Roof structure/representation	flat	differentiated roof structures	real object form	real object form
Roof overhanging parts	no	yes, if known	yes	yes

4.3. LoD 4 to LoD 3 transformation

The major difference between LoD 4 and LoD 3 is that LoD 4 models have building interiors, such as rooms, interior building installations and ceilings. So the transformation between LoD 4 and LoD 3 is basically removing all the interior and changing LoD 4 geometry into LoD 3 geometry. Fig. 6 shows the details of the transformation.

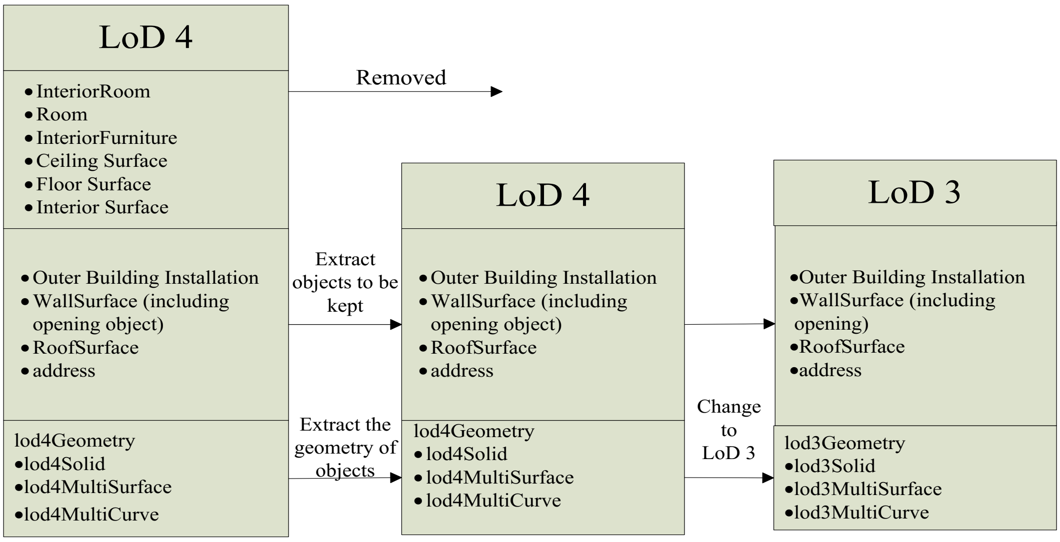


Fig. 6: Details of transforming LoD 4 to LoD 3

4.4. LoD 3 to LoD 2 transformation

There are two major tasks in LoD 3 to LoD 2 transformation: the removal of opening elements (i.e. windows and doors) and finding the exterior envelope of the building. Fan et al. (2009) proposed an algorithm which could automatically extract the envelope of the building by calculating the distances of surfaces to the center of the building. However, this method does not work with buildings with non-convex envelopes. A new scanning algorithm is proposed here which finds the exterior of buildings even with complicated envelope. The scanning grid is generated from an imaginary sphere surrounding the building and each grid will determine at least one exterior surface of the building. The scanning is done on an auto-adjusted fashion and would not stop before finding out all the exterior surfaces of the building. After the scanning, only the exterior surfaces are kept to form the LoD 2 model of the building. Fig. 7 illustrates the details of the process.

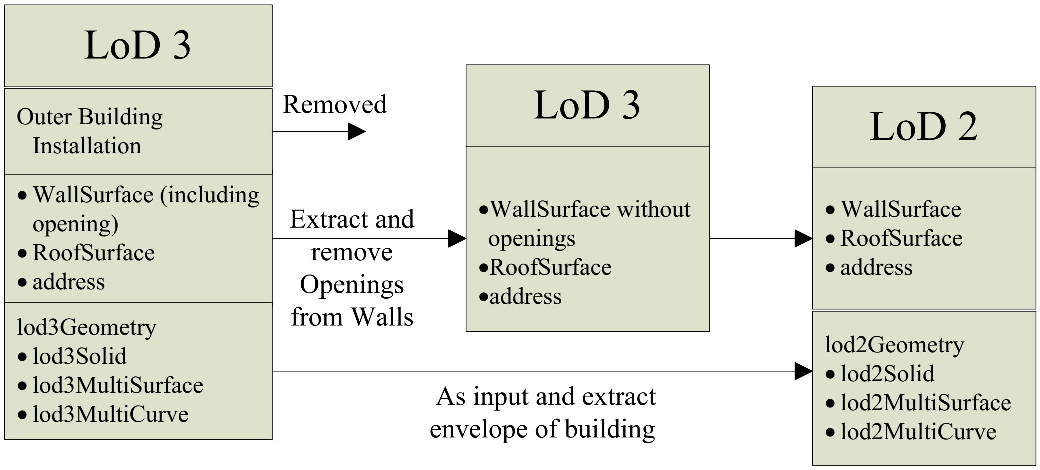


Fig. 7: Details of transforming LoD 3 to LoD 2

4.5. LoD 2 to LoD 1 transformation

Buildings in LoD 1 are boxes without any roof structure. So the LoD 2 to LoD 1 transformation is simply removing all the roof structures and building the envelope for the remaining walls. Although LoD 1 is the typical block model, the shape of walls is still kept in the model. All the remaining surfaces are written into a solid CityGML LoD 1 model.

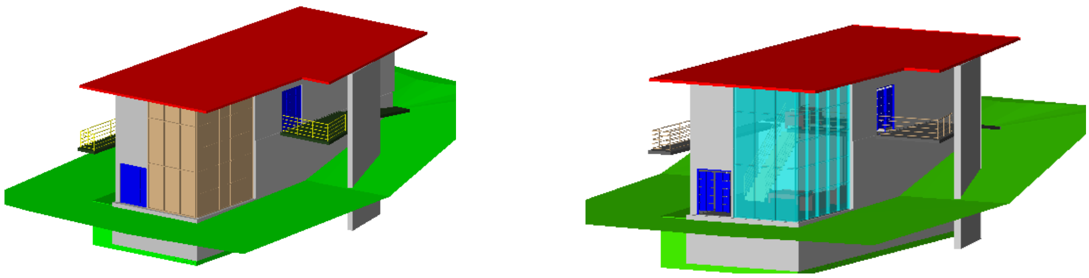
5. DEMONSTRATIONS AND DISCUSSIONS

The proposed framework of transforming BIM into GIS with different LoDs was tested against several models. The programing platform for the testing was JDK 7. JSDAI was chosen as the parser for IFC files and CityGML4j and JAXB were chosen as the parser and generator for CityGML files.

5.1. Demonstration of transforming BIM (IFC) into GIS (CityGML)

The framework of BIM to GIS transformation was tested against several models with different building layout and different components inside the building. The test showed that the translator developed based on the framework could capture all the geometry information of building objects, such as walls, openings, curtain walls, furniture, stairs, railing and structural members. The test result also showed that the proposed framework could capture the terrain information surrounding the building provided by the BIM model. Furthermore, with the help of SCM ADE, the semantic information in BIM models was also kept in the GIS model, which could support further investigations and simulation of the building in 3D GIS system. Fig. 8 shows one of the generated GIS model from BIM. As shown here, the GIS model was almost identical to the BIM model, capturing even the information of furniture inside the building.

The result from our framework was also compared with the CityGML models generated from BIM Server described in (van Berlo and de Laat, 2011). The results are shown in Fig. 10. The figure (c) in Fig. 10 was generated from the proposed framework and the figure (b) was from BIM Server. While our models kept almost all the geometry and semantic information from BIM models, the CityGML model from BIM Server had missing components (i.e. roof, stair and railings). Moreover, the file size of CityGML from BIM Server was much larger than that from our framework. This is mainly because they used triangulation even for walls without holes. The number of surfaces in the model from our framework is much less than that from BIM Server.

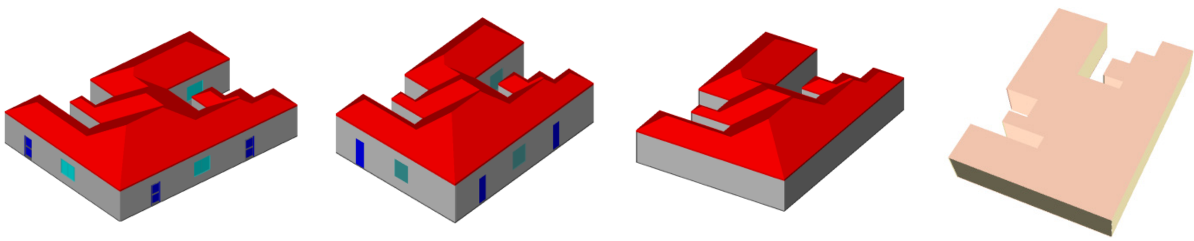


BIM Model in IFC (1024 KB) GIS Model Generated (4027 KB)

Fig. 8: Test result of the framework: BIM model (left) and GIS model (right)

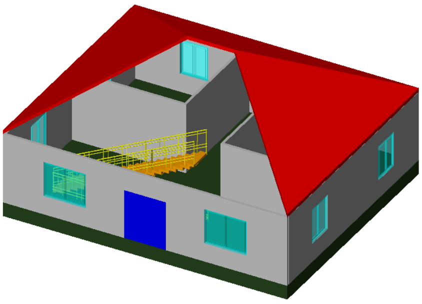
5.2. Demonstration of harmonization between different LoDs in CityGML

The second demonstration was the test of harmonization between different LoDs in CityGML. The generated model from the previous test was always in LoD 4. Using this as the test source, the LoD 4 model ran through the LoD translators and generate 3D GIS building models in lower LoDs. Users could decide whether they want to keep the semantic information about building components or not, even if they were deleted or simplified during the process. Between the transformations from LoD 4 to LoD 3, users were also able to simplify the opening so as to further reduce the file size. Fig. 9 and Fig. 10 illustrate the process of demonstration. The LoD 2 in Fig. 9 also indicates that our scanning algorithm successfully captures the building exterior even for complicated non-convex building envelope.

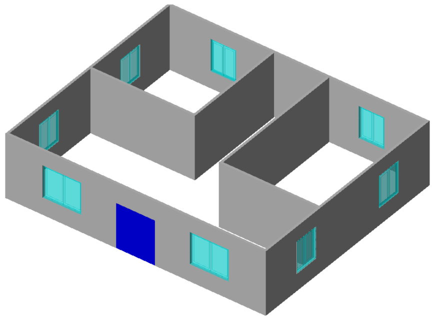


LoD 4 Building Model LoD 3 Building Model LoD 2 Building Model LoD 1 Building Model

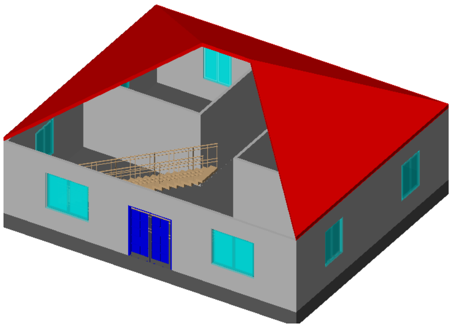
Fig. 9: Demonstration of harmonization between LoDs in CityGML



(a) BIM Model in IFC format (one roof slab hidden) (756 KB)

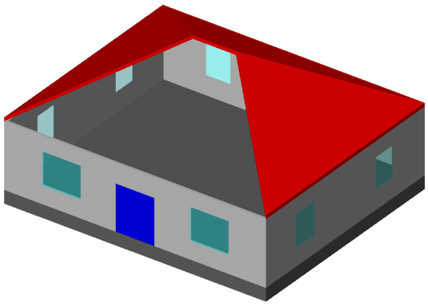


(b) CityGML Model from BIM Server (1030 KB)



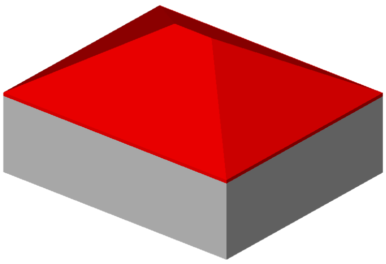
(c) CityGML LoD 4 Model generated (401 KB)

(one roof slab hidden from view)

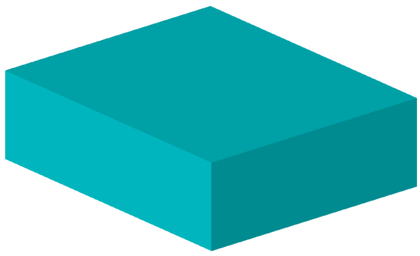


(d) CityGML LoD 3 Model generated (50 KB)

(one roof slab hidden from view)



(e) CityGML LoD 2 Model generated (19.9 KB)



(c) CityGML LoD 1 Model generated (14 KB)

Fig. 10: Comparison with results from BIM Server, as well as demonstration of LoDs transformation

6. CONCLUSIONS

This paper presents a mapping framework between BIM models and 3D GIS models in different levels of detail. The mapping is divided into two steps: firstly, transform BIM models into high level of detail GIS models; secondly, the harmonization between different levels of detail of GIS models is realized. In the first step, this study investigates the reasonable parser design strategies and finds that the Top-down approach is more reliable in the parsing process. In order to achieve a full data mapping and transformation, CityGML ADE called the Semantic City Model (SCM) is developed which captures the inverse and non-inverse attributes from BIM models. The second step involves the strict definitions of different LoDs and the implementation of automatic transformation from higher LoDs to lower LoDs. A new scanning algorithm is proposed to get the accurate building exterior shell. As well as achieving automatic LoDs harmonization, the semantic data is still kept for further use of the generated building model in 3D GIS. In the future, we are planning to use this mapping framework for simulations and investigations of sustainable city design. Using BIM as data source, it is believed that such simulations could achieve higher accuracy.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the support by the Hong Kong Research Grants Council, Grant No. 622812. Any opinions and findings are those of the authors, and do not necessarily reflect the views of the Hong Kong Research Grants Council.

8. REFERENCES

Döllner, J. & Buchholz, H. Continuous level-of-detail modeling of buildings in 3D city models. Proceedings of the 13th annual ACM international workshop on Geographic information systems, 2005 Bremen, Germany. Association for Computing Machinery, 173-181.

Döllner, J., Kolbe, T. H., Liecke, F., Sgouros, T. & Teichmann, K. The Virtual 3D City Model of Berlin-Managing, Integrating, and Communicating Complex Urban Information. Proceedings of the 25th Urban Data Management Symposium (UDMS), 2006 Aalborg, Denmark. 15-17.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. 2008. BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors, Wiley Publishing.

El-Mekawy, M., stman, A. & Shahzad, K. 2011. Towards Interoperating CityGML and IFC Building Models: A Unified Model Based Approach. In: Kolbe, T. H., König, G. & Nagel, C. (eds.) Advances in 3D Geo-Information Sciences. Berlin Heidelberg: Springer 73-93.

Fan, H. & Meng, L. Automatic derivation of different levels of detail for 3D buildings modeled by CityGML. Proceedings of 24th international cartography conference (ICC2009), 2009 Santiago Chile. 15-21.

Fan, H., Meng, L. & Jahnke, M. 2009. Generalization of 3D buildings modelled by CityGML. Advances in GIScience. Springer, 387-405.

Gröger, G., Kolbe, T. H., Czerwinski, A. & Nagel, C. 2008. OpenGIS city geography markup language (CityGML) encoding standard, Open Geospatial Consortium Inc. .

Gröger, G., Kolbe, T. H., Nagel, C. & Häfele, K.-H. 2012. OpenGIS City Geography Markup Language Encoding Standard 2.0, Open Geospatial Consortium Inc. .

Gröger, G. & Plümer, L. 2012. CityGML–Interoperable semantic 3D city models. ISPRS Journal of Photogrammetry and Remote Sensing, Vol. 71**,** 12-33.

Herrlich, M., Holle, H. & Malaka, R. 2010. Integration of CityGML and Collada for High-Quality Geographic Data Visualization on the PC and Xbox 360. In: Yang, H., Malaka, R., Hoshino, J. & Han, J. (eds.) Lecture Notes in Computer Science. Berlin / Heidelberg: Springer 270-277.

Hijazi, I., Ehlers, M., Zlatanova, S., Becker, T. & Berlo, L. 2011. Initial investigations for modeling interior Utilities within 3D Geo Context: Transforming IFC-interior utility to CityGML/UtilityNetworkADE. Advances in 3D Geo-Information Sciences. Springer, 95-113.

Kolbe, T. 2009. Representing and Exchanging 3D City Models with CityGML. In: Lee, J. & Zlatanova, S. (eds.) 3D Geo-Information Sciences. Springer Berlin Heidelberg, 15-31.

Kolbe, T. H., Gröger, G. & Plümer, L. 2005. CityGML: Interoperable access to 3D city models. Geo-information for disaster management. Springer, 883-899.

Lipman, R. 2009. Details of the mapping between the CIS/2 and IFC product data models for structural steel. Journal of Information Technology in Construction, Vol. 14**,** 1-13.

Strzalka, A., Bogdahn, J., Coors, V. & Eicker, U. 2011. 3D City modeling for urban scale heating energy demand forecasting. HVAC&R Research, Vol. 17**,** 526-539.

Van Berlo, L. & De Laat, R. 2011. Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In: Kolbe, T. H., König, G. & Nagel, C. (eds.) Advances in 3D Geo-Information Sciences. Berlin Heidelberg: Springer, 211-227

PART VI: VISUALIZATION AND SIMULATION OF DATA AND PROCESSES

ECOSYSTEM INFORMATION MODELS: VISUALIZING COMPLEX DATA TO SUPPORT COLLABORATIVE DECISION MAKING

Dermott McMeel
Department of Architecture, The University of Auckland, New Zealand

Robert Amor
Department of Computer Science, The University of Auckland, New Zealand

ABSTRACT: *There is considerable interest in 'open data' with many administrations launching, or involved in, programmes to make government data open and available. From geographical information systems (GIS) to infrastructure data and building information models (BIMs), it is believed that access to this data will contribute to productivity and efficiency gains. Yet there remains uncertainty surrounding how stakeholders involved in design, construction and maintenance of the built environment might benefit from this unlocked information. We begin this paper by looking at a specific government initiative providing access to built environment datasets; we investigate and compare the different approaches for accessing this information-base. With speculation that open access will lead to huge benefits in productivity, particularly through interoperability, the second part of our paper implements a system to explore the federation of this data and the results of its interoperation in a collaborative visual environment. While prediction models continue to be problematic when simulating multiple complex and interdependent factors of the built environment concurrently, here we appropriate data and exploit it within decision-support systems. A Systems that provides a qualitative virtual 3D rendering of what is otherwise prosaic or opaque technical information, providing the potential to federate, align and compare otherwise disparate sources of data. Arguably access to open data has not revolutionized consumer computing, but it has played an important part in combination with the emergence of other technologies such as mobile devices, Wi-Fi and location aware computing. Here we critique 'open data' initiatives for design and construction, and ask what part they might play—in combination with other technologies—to help deliver on the promise of productivity.*

KEYWORDS: *Design, Digital Media, Interoperability, Data, Ecosystem.*

1. INTRODUCTION

The analysis of *Open* and *Big* data is a burgeoning field of research, where data is made available to the public it is referred to as being open, when there is a lot of data for processing it is referred to as big. Although both have some bearing on this research we concentrate, in this paper, on the implications of open rather than big data. It is useful to consider for a moment the variety of drivers, interpretations and intentions that inform 'open data' and it's manifold of meanings. Within the context of this paper it is worth reflecting on open data in relation to *governance* and *open source*. The former having its roots in the freedom to access information through the likes of the freedom of information act (FoI), and the latter largely informed by freedom to use, share and modify some digital *goods*. While these are not necessarily oppositional intentions, they are clearly ideologically different; the applications developed through this research as described later in section 3, illustrate the impact these different ideologies have on the extent to which data can be shared and used. The term *open data* is used very generically and often woven into promises to improve productivity and value. In New Zealand the Productivity Partnership and GeoBuild strategy are bringing the subject of open data into sharp relief for architecture, engineering and construction (AEC), where a 20% productivity improvement for the AEC sector is targeted for 2020. Yet already there is skepticism emerging within the field and some nascent work suggesting gaps between the promises and benefits of open data (Janssen, Charalabidis & Zuiderwijk 2012). *Productivity* is also a generic term; analysis has revealed dozens of disparate factors contributing to notions of productivity in the AEC sector (Borcherding, Palmeter & Jansma 1986). In fact as the number of notable projects outlined in Table 1 attest, there are unique measures of productivity appropriate within different situations. The trend to improve productivity continues with the formation of the UK BIM Task Group, who ring-fence *reduction to capital cost* and *carbon burden* as their metrics; interestingly they have almost completely dispensed with using the word *productivity*. Continuing to reflect on Table 1 we might also note the focus is almost exclusively on national and multi-national companies undertaking projects of significant

Citation: McMeel, D. & Amor, R. (2013). Ecosystem information models: visualising complex data to support collaborative decision making. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

scale. Countries like New Zealand, for example, have considerably different market forces to Europe or America, it should not be assumed the cost/benefit ratios from one country can, or should, be automatically applicable to other geographical or economic contexts.

Table 1: Projects citing productivity improvements (reproduced with permission of V. Gonzalez).

Country	Project Name	Project Type	Type of Improvement			
			Cost	Time	Productivity	Others
U.K	Barts And The London	Commercial multi project	22% cost-benefit	6 weeks saved	Clear deliverables & procedures	Improved safety for FM and Users
Denmark	New HQ for Engineering consultant Ramboll	Office Building	Direct benefit DKr 3.8 million	Saving in time for zero RFI		
India	3x660 MW Supercritical Thermal Power Plant	Infrastructure project	Under budget	Reduce engineering time by 10 percent		Multiple design simulation
Brazil	Matec Engineering	Construction Project	Enormous saving	Saving 40 percent in time	30% material saving	
Finland	Aurora 2	Education facility at Joensuu University	Under Budget	Saving design change time	Energy efficient	Sustainable features

1.1 What is Open Data?

The general supposition of open data is that information generated in one place is useful in others. Currently access might be restricted, prohibited or laborious, and by making it open individual stakeholders can increase speed, innovation or enable them to do more with less. Government and building industry partnerships are thus approaching the concept of *open data* with much in common with the open source movement, rather than traditional government freedom of information (FoI) acts, and we feel there are important distinctions here.

Open data is based on the presumption numerous people will access, modify and redistribute some digital goods, which can cause fragmentation; a phenomenon whereby multiple versions of a *thing* cause some versions of the thing to be incompatible with others. For example phones running the Android operating system have been criticized for suffering from fragmentation, where software applications run inconsistently across different models of handset. Thus one of the main challenges with open data is tracking access, problems, reliability, changes and version control. The open source movement has developed numerous version control systems to do this, such as Git and Subversion. GitHub (https://github.com/) is an online version of Git that assists collaboration and project management, it allows complex code to be changed and tracked in relation to how it works—or no longer works—with other pieces of the project which are also changing concurrently. Git has even been appropriated as an issue tracker for house maintenance (McMillan 2013) and elsewhere the authors are exploring if it has merit as a tool for tracking the data and its changes during building design and construction. Essentially the open source data ideology has evolved systems designed to track the changes and relationships within and between complex dynamic datasets. Open data in relation to governance is somewhat different with its roots generally found in various country specific FoI acts, which enable access to specific static and usually historic documents. Accessing information through FoI can be laborious, although open government data is a notable improvement on FoI it has emerged from a culture of simply providing access to specific information. What will be revealed in this paper through the development and analysis of two software applications drawing on open data is the different cultures that underpin the provision of data are highly influential; they ultimately have considerable bearing on what can be meaningfully achieved.

Elsewhere the authors have explore the impact of the materiality of data on design and making processes (McMeel & Amor 2013) and our findings here continue to support the suppositions put forward by Paul Dourish that data storage and rendering are not incidental, they are fundamental and influence understanding and knowledge practices that surround them (Dourish & Mazmanian 2012).

1.2 Two Software Applications

An initial brainstorming session attended by designers, an architect and computer scientist revealed various personal frustrations with professional and consumer activities. How they are laborious and time consuming, or even in light of current services and data available online they remained unchanged for decades. Two of these scenarios, one oriented towards professional designers and one directed at house buying consumers, were chosen as test cases because of their potential to scrutinize suppositions regarding open data within the AEC industry. The first scenario explores how to improve the process of site analysis, which is a specific activity undertaken by architects at the early stages of building design. The second scenario investigates improving how prospective house buyers can evaluate the suitability of prospective house locations.

In a break from conventional methodology we did not establish a brief or set of functions and interaction capabilities; we instead chose to outline a narrative for both the professional and consumer scenario. Our decision was in part informed by the sixth sense transport research project (http://www.sixthsensetransport.com/) that uses similar approaches to successfully keep projects and research people-centered. Where research is overtly technical in nature, it is all too easy to lose sight of the goal and instead focus only on the development of technology. The scenarios provided a qualitative rather than a quantitative framework within which the designers considered choices and decisions. Through this work we aim to advance generic discourse and supposition that surrounds the provision of open data to increase productivity. By identifying and focusing on these two scenarios we look at explicit situations and how they might benefit through access to available digital information. The scenario for the professional application was that an architect prior to visiting site could—through this software application—access data that is usually time consuming to gather and aggregate. Such as topology, soil type and building usage; this data could be rendered to build an overview of the site. The scenario for the consumer application was software that a house buyer could use to identify prospective house locations and be quickly presented with information that enables evaluation and comparison. In the following sections we will outline the data that was available at the time of writing, and then explain the software implementations before finally answering the following questions. Are current open data initiatives adequate? What part might they play in improving productivity in the AEC sectors?

2. A TYPOLOGY OF DATA

There is an ever-increasing variety of data related to the built environment. As well as Google Earth and Maps, there are localized providers of amenity databases and service such as Yellow.co.nz, Zenbu.co.nz as well as government initiatives. Whereas commercial providers like Google invest heavily in the rendering of data to make it useful, visualization of data is not the core business of government data providers. Consequently government occasionally comes under criticism for providing opaque and unintelligible data (Smith 2012). Yet it can be highly revealing and valuable, so in this section we will consider the data available under three categories, *government silo'd, government managed* and *commercially provided*.

2.1 Government Silo'd Data

The word *silo* refers to the storage structure of data, one that requires traveling deep into a silo to access data and to leave one silo entirely to journey deep into another. This leaves data mining difficult and time consuming. Even where governments provide dedicated data sites such as (https://data.govt.nz/) it can be difficult to find what you are looking for. With a data silo a number of generalizations can be made. First, the data is typically available in a number of file formats such as excel spreadsheet (XLS), comma separated variable files (CSV) or a portable document format (PDF). Second, it is unclear if said data is stored in databases and automatically exported in the requested format or previously saved in these formats and stored on a server until requested. Third, in these instances data usually requires manual *point and click* to download the data to your computer hard drive. Data in PDF format is difficult to mine with computers; XLS and CSV are reasonably common file standard for data and are machine readable. CSV was the format utilized most often in this research, although as we shall see during our analysis it was not without problems.

Relatively speaking, because it is not machine readable, a government data silo presents obstacles for data access when compared with commercially provided systems that use application programming interfaces (APIs). Access requires manual intervention by a person to physically *point and click*; this limits utilization by automated and interoperable data systems. Yet governments hold valuable statistical information on, for example, crime, mortality and changes to land use; data that is useful in grasping historical trends, current state of, and potential future directions for any given area. It helps to grasp a location's flavor or to use the German term *gestalt*, which Oxford English Dictionary defines as a '*shape, configuration, or structure which as an object of perception forms a specific whole or unity incapable of expression simply in terms of its parts'*. The point being the cognitive impact of a particular combination of datasets—or overview—can be qualitatively different to analyzing them in isolation. What is often called the 'overview effect' (White 1987), was originally coined in referring to the impact on astronauts of seeing the earth from space:

The Overview Effect is the experience of seeing the Earth from a distance, especially from orbit or the Moon, and realizing the inherent unity and oneness of everything on the planet. The Effect represents a shift in perception wherein the viewer moves from identification with parts of the Earth to identification with the whole system. (White 1987, p. 38)

While the Overview Effect is best understood through narratives from astronauts, it is also useful as a way to frame the problem of our data rich world, where it is increasingly difficult to get an overview when overwhelmed by granular and detailed information. This position has been advance by Chris Speed who suggests our data intensive environments produce an *Underview Effect*, which provides a greater awareness of social and geographical context (Speed 2010). Both effects are valuable within the context of our scenarios, however it is the Overview Effect that is harder to achieve through data, as data—according to Speed—is predisposed to producing an Underview.

2.2 Government managed

Moving on from government silo'd data we found several sources of information best described as government managed. Where a geo-data management service is used to organize and facilitate access to information. In New Zealand, government departments such as Land Information New Zealand-LINZ (http://data.linz.govt.nz/) and research institutes like Landcare Research Information System (http://lris.scinfo.org.nz/) have deployed a system developed locally by Koordinates (http://koordinates.com/); an award winning system (Sweeney 2012) designed specifically to manage geo-data.

While the core functionality of the Koordinates system is data management rather than visualization, however the inclusion of a map makes understanding the geography of the data much easier. Still, with over one thousand datasets available on LINZ, knowing which to access continues to be challenging. A distinct advantage of the Koordinates system is that it provides an API, enabling data access and manipulation without the need for manual download. This creates the possibility of developing software and mobile applications that can communicate with, but created independently from, the data; as long as the data management is kept up-to-date, the application will be up to date. The data is always presented in a consistent format in this case it can be called as extensible markup language (XML) or JavaScript Object Notation (JSON), both of which are international and widely used web standards. This consistency means manipulating the managed data is much easier and, we found, provides greater flexibly than silo'd data.

2.3 Commercial Data

The final category of data is *commercially provided*; this data usually provides information on local amenities such as bars, restaurants, shops etc. It is made available by commercial groups such as Google, Localist.co.nz or Zenbu.co.nz, often gathered using a variety of collaborative or crowd sourced techniques the data also changes more frequently than government data. It is highly sought after as it gives feedback on currently available amenities. Much like the Koordinates systems discussed in the previous section, these providers also typically provide powerful APIs to enable sophisticated manipulation of their datasets.

Returning to our test case scenarios, both developers agreed it was necessary to draw on the commercially provided data provided by Zenbu.co.nz, however the developer of the house-buyers application would use Koordinates and LINZ managed data while the developer of the professional site analysis application used government silo'd data, in the following section we will compare and contrast these two applications.

3. SOFTWARE IMPLEMENTATIONS

The two scenarios and software applications being discussed in this section are technically quite similar. Both visualize geo-data, in some cases the same geo-data, in a virtual environment to assist individuals or groups of people making decisions or judgments about specific places. The difference between the two is best articulated in terms of White's *Overview Effect* and Speed's *Underview Effect* discussed earlier in this paper. The consumer application targeting house buyers will need to render this granular data qualitatively providing the user with an overview to make quick comparisons between locations. The professional application directed at professional architects will need to present the *underview* that we have just discussed and the detail of amenity and geographical context for it to be of any use within an architectural site analysis. Both developers chose to use the Processing software (http://www.processing.org/) to develop their prototype applications.

3.1 Professional site analysis application

Without wishing to overstate the obvious, the aim of a site analysis is to gather pertinent information on a place that will help inform the design of a building intended for that specific place. With the exception of procuring information through geographical information systems (GIS), the process of gathering data for a site analysis is much the same as it was twenty years ago; a large portion of relevant data (foliage, building typology, traffic/pedestrian flow, local amenities) is gathered through visits to site. Although much of this data is available online, the aim of the professional application was to allow a user to focus on a particular location and render pertinent data. There was no presumption this application would replace a physical site visit, rather, could accessing and visualizing soil, contours, land use and amenities in this way be more efficient?

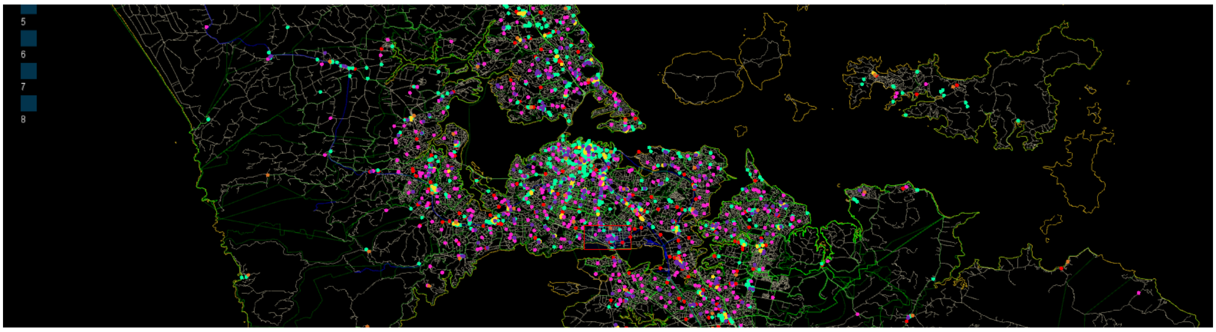


Fig. 1: Government silo's data and LINZ data rendered from downloaded CSV files.

Initially obtaining the data was relatively straightforward, data was downloaded as CSV files that would be imported into the application. Even at this early stage a number of problems began to emerge, beginning with legibility and data integrity. Each downloaded data set was quite different with little consistency in format and data identifiers were overtly cryptic. For example the column header for the land use data set were mostly meaningless without further explanation: OBJECTID, TYPE, LEGEND, LUC1C, LUC1S, LUC1UU, LUCPL, LUC2C, LUC2S, LUC2UU, LCORRC, LCORRS, LCORRU U, LCORRQ, LUC, LCORR, WKT. When this was deciphered the data was still returning an error within the application because of particular encodings used for some strings of characters within the CSV file. These had to be manually replaced within text editing software before the data could be used reliably for a virtual rendering of the city.

Having made the data machine readable a number of issues continued to hinder progress on the professional application. In certain data sets urban parks were marked as single GPS points rather than a bounding polygon that would helpfully represent the geographical extent of the park. Also the road networks were stored as vector lines and in the absence of contour data – which was not free but would require a fee to download. The developer invested considerable time to return the rendering of the data in Figure 1. In this rendering land usage is color coded and a key with checkboxes is being implemented on the left hand side of the image to enable layers of data to be turned on and off.

In summary, although government initiatives are making much data available, where it is provided in these governments silo's (XLS, CSV) is was not directly machine readable; it required manual downloading and editing. The professional application, although functional, did not progress as far as was anticipated because of the numerous data irregularities and inconsistencies. It was also necessary to hard code the data into the application, which will result in it becoming obsolete as the data becomes outdated unless the application is manually updated.

3.2 Consumer house buying application

Turning to the house-buyers application, one of the authors purchased a house just prior to this research. The Auckland property market is highly competitive, by way of an example it is not unusual for houses to be sold within one week of listing and before any public viewing of the dwelling has been possible. In such a marketplace it is difficult to gather enough information and get to know a neighborhood within a useful timeframe before committing to a purchase. With this scenario we knew the relevant data was available online, the aim of the house buying application was to give a user a visualization of a suite of data sets that would otherwise take considerable time and research to obtain. It was an attempt to provide a rendering of a qualitative overview, the gestalt, of highly granular and detailed information. The strategy adopted by the developer of this application was different to the previous professional application; it was decided in this case to use API's where possible. Although during development some historical seismic data from GeoNet was hard coded to show a chronology of seismic activity across the country in combination with the other data. In the finished application (Figure 2) there was virtually no hard coded data present, it was all drawn dynamically when required from Google Maps, Koordinates, LINZ and LRIS.

Fig. 2: House buying application showing closest amenities, supermarkets and school zones for two locations.

The methods for data appropriation used in this application were considerably superior to those used in the first application, although the data required for the first application was not necessarily available through one of the API enabled sources. This application only requested data from data sets when a location was selected on screen, thus it was highly efficient and fast. It also remains current, the amenity data is drawn from Zenbu.co.nz and thus continues to be updated and relevant.

4. CONCLUSIONS

Let us return to our opening question – what part might open data play in the promise of productivity? Firstly *open data* and *productivity* have been found to be overtly generic and ill-defined terms. Our opening reference to Borcherding analysis of *productivity* shows dozens of factors that potentially contribute to productivity. What is required initially is specificity, the UK BIM Task Group has, for example, ring-fenced capital cost and carbon burden to be the national metric for the purposes of focusing actions, research and initiatives. Although there might be disagreement over the relevance and impact of these factors, we can agree that providing such a focus, for such a complex and varied industry, is necessary to mobilize key stake-holders and, returning to the theme of this paper, identify what the information and inter-operability requirements are, and in what roles do they need to be implemented. Although we found an abundance of information, it did not always meet the inter-operability needs of our scenarios. Scenarios, which are modest in comparison to the mobilization that will be required for government initiatives.

Turning to our two understandings of open as being either (1) Informed by the culture of Freedom of Information (FoI) or (2) Informed by the open source movement, the future of design and construction will not be transformed by open data driven by the culture of Freedom of Information. Data from silo'd government repositories required manual downloading and usually manual editing. In the race to provided easy to use tools and services for the industry, this is highly problematic. Where our scenarios benefited substantially from the provision of data it was informed by the open source movement. A modest easy to use consumer application was designed and deployed that continues to return relevant and current information as it accesses the reliable and current data provided by Koordinates, LINZ and Zenbu through their API's. It has proven so successful in fact that, at the time of writing, the developers are exploring options for commercialization of the consumer application where this information can be accessed through a mobile device. All of this is possible as there is no inherent obstacle within the data or its access that impedes these entrepreneurial initiatives. Our unconventional approach to focus on two scenarios proved highly valuable. It prevented the technology taking center-stage and helped maintain a focus on the practices and the needs of the users of the technology. One issue that remains unresolved surrounds the problem of rendering *fuzzy* data. Some of the highly critical government data, such as school zones and school decile rating (a New Zealand method for ranking school performance) changes occasionally. When data is rendered it becomes fixed and yet it is important to convey that some information is fluid and subject to change, particularly highly valued information.

In summary there remains much hyperbole around open data and productivity, what is clear from this modest programme of research is that simply encouraging or mandating that information is provided will not necessarily guarantee the data access or inter-operability that researcher, innovators and companies will need to meet the approaching industry challenges. Although the problems cannot be completely predicted and their answers not known, we will be more likely able to deal with them given access to open data as provided by Koordiates, LINZ and Zenbu. In fact at the time of writing the US government has mandated that government data will not only be open but *machine readable*. While our test cases are admittedly modest in scope the developer of the consumer application is investigating commercial development. Perhaps the most pertinent point is when data is opened through powerful and flexible APIs and managed by people or organizations with key competencies in the management of geo-data it becomes possible to conduct research and develop services, devices and applications that address these challenges. It becomes possible to identify problems and develop solutions, and it would appear to be the means by which we will advance the industry rather than the obstacle that impedes it.

5. ACKNOWLEDGEMENTS

The authors would like to thank Paul Organ and Kurt Meyer who developed the two software applications during the University of Auckland's Summer Scholarship programme, as well as Hamish Campbell from Koordinates.

6. REFERENCES

Borcherding, J. D., Palmeter, S. B. and Jansma, G. L. (1986). Work force management programs for increased productivity and quality work, *EEI Construction Committee Spring Meeting,* 4–9.

Dourish, P. and Mazmanian, M. (2012). Media as Material: Information Representations as Material Foundations of Organizational Practice, In P. Carlile, D. Nicolini, A. Langley, & H. Tsoukas (Eds.), *Perspectives on Process Organization Studies Vol 3: How Matter Matters: Objects, Artifacts and Materiality in Organization Studies*, Oxford: Oxford University Press. Retrieved from http://www.ics.uci.edu/~mmazmani/Site/Publications_files/dourish_mazmanian_materiality_final_book_submission.pdf

Janssen, M., Charalabidis, Y. and Zuiderwijk, A. (2012). Benefits, Adoption Barriers and Myths of Open Data and Open Government. *Information Systems Management*, Vol. 29, No. 4, 258–268. doi:10.1080/10580530.2012.716740

McMeel, D. and Amor, R. (2013). Fabricate It, Paint It – And Don't Wait up: Separating Fact from Fiction in Digitally Sponsored Fabrication. In J. Zhang & C. Sun (Eds.), *CAAD Futures,* Berlin: Springer Verlag, 149–158.

McMillan, R. (2013). This Old (Open Source) House: Man Renovates Home on GitHub, *Wired,* Retrieved April 17, 2013, from http://www.wired.com/wiredenterprise/2013/01/this-old-house/

Smith, M. (2012). The big debate: open data, *The Guardian,* Retrieved April 17, 2013, from http://www.guardian.co.uk/public-leaders-network/2012/aug/20/big-debate-open-data

Speed, C. (2010). Developing a Sense of Place with Locative Media: An "Underview Effect", *Leonardo*, Vol. 43, No. 2, 169–174. Retrieved from http://www.mitpressjournals.org/doi/abs/10.1162/leon.2010.43.2.169

Sweeney, S. (2012). NZ Gov wins prestigious spatial award, *FutureGov*, Retrieved April 17, 2013, from http://www.futuregov.asia/articles/2012/nov/23/nz-gov-wins-prestigious-geospatial-award/

White, F. (1987). The Overview Effect, Boston: Houghton Mifflin Company.

INTEGRATED VIRTUAL REALITY AND DISCRETE EVENT SIMULATION METHODS FOR PRODUCTION SYSTEM RESEARCH IN CONSTRUCTION

Ury Gurevich & Rafael Sacks
Technion – Israel Institute of Technology

ABSTRACT: *Researching the behavior of production systems in construction is challenging because outcomes depend not only on production system design and on control strategies, but also on the decision-making behavior of works managers, crew leaders and suppliers. People make decisions within their context, and with limited and often uncertain information. This is especially true in the case of construction projects, where production is dependent on close coordination between multiple independent subcontractors. Theoretical models of the systems are limited if they ignore the human element, or if they assume rationality in decision-making. Thus experimental setups designed to test proposed production control systems or strategies should incorporate live experiments with human subjects. Virtual reality (VR) environments linked with discrete-event simulations (DES) provide an excellent platform for this kind of experimental setup. They enable, for example, experiments to compare performance with and without proposed information systems or other tools. We review the state-of-the-art in research of production control systems in construction management, with emphasis on VR and DES. We describe the experience gained in using a hybrid 'Virtual Construction Site' (VCS) system in which construction crew leaders were immersed in a virtual reality (VR) CAVE where they worked in a DES controlled site. The VCS proved its efficacy by allowing the researchers to observe, record and analyze the decision-making behavior of human subjects in a controlled environment, with high accuracy and in relatively very short times.*

KEYWORDS: *Computer aided simulation; Construction management; Discrete-event simulation; Experimentation; Production system design; Virtual Reality.*

1. INTRODUCTION

Production systems in construction are, in general, particularly wasteful of resources due to the specific challenges of achieving smooth production flows in the complex, uncertain and variable conditions that are typical of construction projects (Koskela et al., 2012). Recognition of the potential to remove waste has led to the rise of many proposals, from practitioners in industry and from the construction management research community, for improved techniques and tools for production control. Among them, location-based management systems (LBMS) (Kenley and Seppänen, 2009) have been proposed to replace traditional tools such as the Critical Path Method (CPM), the Last Planner System™ (LPS) (Ballard, 2000) has been adopted widely for production flow control, and relatively simple kanban and CONWIP approaches have been implemented. A variety of software applications have been developed for scheduling, supply chain management, project collaboration and information sharing, and for implementing the LPS. Examples of these include the i-Booth (Ruwanpura et al., 2012), the KanBIM system (Sacks et al., 2010) and ourPLAN (Ourplan, 2013). The common goal of the systems is to improve production flow – reduce waiting times for crews, deliver materials just-in-time and in the right quantities, optimize use of equipment and reduce inventories of materials and of work in progress.

Research and development of these systems and tools requires the ability to test their efficacy. However, this is difficult for a number of reasons. Construction projects are built by complex organizations in which many independent designers, subcontractors and suppliers have different and sometimes conflicting interests. In such systems, it is very difficult to predict the effect of a proposed production control system, especially due to the often inexplicable nature of human behavior that can be irrational and strongly influenced by the context and circumstances. Yet it is essential to consider the human element when a production control system is tested.

In the following sections of this paper we first review the use of various research methods for research in the development of production control systems for construction. We then discuss the use of discrete-event simulations (DES), considering their limitations as well as their benefits. Against this background we describe a novel

Citation: Gurevich, U. & Sacks, R. (2013). Integrated Virtual Reality and discrete event simulation methods for production system research in construction. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

experimental approach that was sought to exploit the benefits of discrete-event simulation (DES) but nevertheless allow observation of the behavioral aspects. A hybrid 'Virtual Construction Site' (VCS) system was devised and implemented, in which construction crew leaders were immersed in a virtual reality (VR) CAVE where they worked in a DES controlled site, with and without the production control system that was the subject of the research.

2. RESEARCH OF PRODUCTION CONTROL SYSTEMS IN CONSTRUCTION

Much construction management research requires evaluation of the impact of innovative interventions on the way that work on site is planned, controlled or executed (Xue et al., 2012). In this section, we review the different methods that have been used to perform research of this kind in order to establish the background for comparison among them and for evaluation of the relative advantages and disadvantages of the methods that use VR, DES and integrated computer systems.

2.1 Field studies

The most apparently obvious approach to perform such experiments is to test the innovation directly on one or more construction sites. This requires establishment of a control baseline by measurement of key performance indicators on site, application of the innovation, and then measurement of the indicators to determine the impact.

However, experimentation on a working construction project site presents numerous challenges to the researcher. Data collection may require frequent and intensive observations of workers on site, using work study methods. The duration of measurement that is needed is often long, measured in weeks or months. Where the research requires comparative measurements of productivity, factors such as weather, absentee workers, delays in material deliveries, unexpected unavailability of working space, design errors, lack of information, are but a few of the factors that can introduce sufficient noise to render measurements inaccurate or unreliable. The inability to replicate the experiments with the same boundary conditions precludes the possibility of collecting sufficient samples to reduce the statistical significance of these anomalies. Focus groups and in-depth interviews are often used therefore instead of, or in addition to work studies.

Examples of experimentation in the field are therefore relatively rare. Ergen et al. (2007) tested a system based on radio tagging (RFID) and GPS for tracking precast concrete elements, and Teizer (2008) examined the use of various technologies for monitoring workers to improve safety in construction. Both of these focused on monitoring technologies rather than production control systems per se, and had short durations. Chen et al. (2002) provide a good example of extended measurement of an intervention on a construction site, in which the quantities of material wasted were measured over three months in both a control and an experimental building to test the impact of a bar-code material consumption control system.

2.2 Case studies

Given the difficulties listed above, case studies have become a preferred method for investigating the impacts of construction production systems. Examples abound: Khanzode et al. (2005) reported a case study exploration of the use of lean methods and virtual design and construction on a hospital project; Pheng and Hui (1999) researched the use of the just-in-time (JIT) philosophy in construction; Seppänen (2009) used three detailed case-studies to evaluate the use of location-based planning and control systems; and Walsh et al. (2004) evaluated the relationships between demand and inventory in governing the supply chains for capital projects.

By their nature, the case study research projects report the results of interventions that have been implemented in a site or company over some time, usually many months or years, with great effort. Their main drawback, however, is that they do not offer a baseline for comparison of the measures of apparent improvements. It is not possible to say by how much the performance has improved, because there is no alternative process – one cannot in general determine what the outcome would have been without the intervention. Even fairly similar construction projects cannot afford direct comparisons because of the multitude of factors that differ across construction projects. It is also not possible to test variations of the intervention.

2.3 Role—playing simulations

Role-playing simulation games can be used for experimentation. Although their use is common in management training, they are less commonly used for research. Some, such as the PTB Sandbox (Shtub, 2012), the MERIT game (MERIT, 2012), and SIM LEAN (CMB, 2010), use computer interfaces to engage players and perform background simulations. Others, such as LEAPCON and the 'Parade of Trades' were designed as 'live' simulations (without computers), although both have been modelled with discrete event simulations (Sacks et al., 2007, Tommelein et al., 1999). The primary advantage of such games is that they engage human subjects, so that unpredicted or unexpected behaviours can emerge. Naturally, the onus is on the researcher to establish that the simulation situations are sufficiently similar to the simulated reality if the results are to be considered applicable to the real world.

2.4 Discrete event simulation

Discrete event simulation (DES) is an alternative approach, offering a ‘clinical’ way to perform such experiments. A computer simulation model of the existing workflow is implemented and control measurements are made through multiple replications of the system (Martinez and Ioannou, 1999, Halpin, 1977). Next, the model is changed to reflect the new process, subject to the intervention that is being tested. Running the revised simulation through multiple replications then provides a new data set that can be compared to the control data, enabling the experimenters to draw clear cut conclusions about the difference in performance between the two scenarios.

The use of computerized DES for research in construction management began with Halpin's introduction of the CYCLONE system (Halpin, 1977). Since then, numerous systems have been built and used for a variety of applications in construction operations research. Examples include RESQUE and CIPROS, each of which extends the capabilities of CYCLONE by adding increasingly more powerful capabilities for modelling constraints related to the resources (Martinez and Ioannou, 1999), and STROBOSCOPE, which was designed for modelling complex construction operations and resolved some of the limiting assumptions of CYCLONE (Martinez, 1996).

DES has also proved to be a popular tool for research of production system design and of production control systems. (Farrar et al., 2004) described how lean production principles could be structured in a generic fashion in construction simulations, and showed how they could be used to achieve smooth flow in roadwork projects. LEAPCON (Sacks et al., 2007) was a simulation extension of Sacks and Goldin's model for lean apartment construction. Based on the airplane game, it simulated the process of construction of an 8-storey building with 32 apartments. The goal was to investigate the effect of three lean production principles (buffer size reduction, pull flow and multiskilling). The Parade of Trades (Tommelein, 1998), is another example of DES use; it shows the impact of variations in the production rates of individual work stations on the overall workflow of a production line that contains multiple stations. Brodetskaia et al.'s (2011) workflow model shows clearly and explicitly the impact of re-entrant flow of crews in a large residential project, allowing experimentation with different policy heuristics for determining crews' behaviour in terms of selecting and starting work.

The method has numerous advantages: it affords complete control of all of the experimental parameters; large numbers of experimental runs can be made in relatively short periods of time; data collection is reliable, accurate and cheap; the net impact of the innovation can be measured precisely; and the systems can be calibrated as needed. The main problem in this approach is that the behaviours of the actors in the process must be pre-programmed. The possible decisions that a ‘human’ actor can take are modelled by probability distributions that select, on the basis of random inputs, which decision will be made in any given situation. An implicit assumption behind this is that the experimenters can predetermine the range of possible individual behaviour patterns. The use of discrete event simulation also precludes the possibility of learning anything about the ergonomics of the innovation or about peoples’ attitudes to it. People’s responses to unexpected events or unstructured problems cannot be explored.

2.5 DES Systems Integrated with CAD and VR Interfaces

Many researchers have added graphic user interfaces to DES applications, using either CAD, game engines or other virtual reality tools. In one example, (AbouRizk and Mather, 2000) integrated simulation modelling with 3D CAD. Their application enabled comparison of different earthwork loading methods for a specific site represented in a CAD model by sharing information between the two distinct systems. This simplified operation of the simulation and made its results more easily accessible to its users. The VITASCOPE application (Kamat, 2003) provided a tool for visualization of the results of simulations by animating the processes in 3D virtual displays, but it was limited to post-processing – a simulation could only be reviewed once it had completed.

Rekapalli and Martinez (2009) extended that capability by integrating a discrete event simulation system with a VR animation environment that also enabled user input at runtime. In this work, they applied the ideas of 'Visual Interactive Systems' (VIS) developed in the 1970's and 1980's (Bell and O'Keefe, 1986) to the domain of discrete event simulation in construction management. Their premise was that "interaction capabilities can enhance the process of model validation and ultimately lead to achieving model credibility"; one of their primary goals was to improve the acceptability of simulations as tools for making decisions about production processes, especially for practitioners.

The Virtual Construction Site (VCS) (Sacks et al., 2012) also uses the VIS approach, but it was developed with a different purpose: to provide an experimental test-bed to test the efficacy of production control systems through experiments with human subjects. As such, it features the technological innovation of interfacing not only with the subject, but also with the prototype control system software. Thus it allows users to interact with the control software concurrently with their interaction with the VR and DES environment. The VCS setup is described in more detail in the next section.

2.6 Critical comparison of common research methods

Table summarizes the methods classified and outlined in the five groups above, listing advantages and disadvantages of each approach. Naturally, not all methods used in practice conform strictly to the groupings. The methods adopted in specific projects may exhibit overlap among them.

Table 1: Advantages and Disadvantages of various research methods

Research Method	Advantages	Disadvantages
Field tests with observations on site; focus groups and in-depth interviews with subjects	1. Direct observation of subjects' behaviour within the work environment and context. Attitudes and opinions can be explored. 2. Progress data is accurate and reliable. 3. Reasons behind behaviour and verbal responses can be clarified. 4. Use of appropriate technology can enable continuous and long-term observation/recording of data.	1. Requires extensive resources for observation. Sampling is often used instead of continuous measurement. 2. The presence of observers can influence subjects' behaviour. 3. Requires long-term observation, because events of interest occur randomly and may be infrequent. 4. Researchers have little or no control of the many external parameters affecting performance. 5. Requires intensive effort to apply the intervention in the test site. 6. Multiple periods of observation are needed for recording baseline and experimental conditions. 7. Experiments cannot be replicated with the same boundary conditions.
Case studies using interviews, questionnaires and focus groups/ workshops	1. Research is based on production-scale implementations of the intervention. 2. Data is drawn from subjects' experience and practices. 3. Cases can provide data sources from which further analysis can be made. 4. Because case studies build on actual practices and experience, they can be linked to action and their insights contribute to changing practice. 5. Results can be persuasive and accessible because the data are close to the audience's experience.	1. The very complexity of the case can make analysis difficult. Relating causes and effects can be challenging. 2. Data is often only retrospective. 3. The researcher's involvement raises questions of objectivity. 4. Variations of the intervention cannot be tested for. 5. Requires proof of generality of cases because conclusions must be generalized from specific instances. 6. Dependent on prior implementation of the intervention being studied.
Role-playing simulations	1. Relatively few resources required. 2. Multiple replications are possible. 3. Permutations of the experiment can be tested.	1. The outcomes can be highly influenced by the mentor. 2. Subjects may focus on their assigned perspective and miss the opportunity to

Research Method	Advantages	Disadvantages
	4. Allows control of the external factors influencing the behaviour. 5. Subjects can be de-briefed to learn about their motivations. 6. Element of reality is compatible with principles of constructivism. 7. Subjects responses to unexpected events or unstructured problems.	relate the simulated conditions to their work contexts. 3. Players are human – although the rules are clear, players can make independent decisions that change the results 4. The number of runs is limited by the availability and stamina of players
Discrete Event Simulation (DES)	1. Experimenter has complete control of all of the experimental parameters. 2. Large numbers of experimental runs can be made in relatively short periods of time. 3. Data collection is reliable, continuous and accurate. 4. Simulation is relatively cheap. 5. The net impact of the innovation can be measured precisely. 6. The systems can be calibrated as needed. 7. Multiple permutations of a system can be experimented with.	1. The behaviours of all of the actors in the process must be represented by snippets of software code and must be pre-programmed. 2. Assumes that the experimenters can establish, in advance, what factors influence the actors' decisions and the full range of possible behaviours and outcomes. 3. Precludes the possibility of learning about peoples' interactions with or attitudes to the innovation. 4. People's responses to unexpected events or unstructured problems cannot be explored. 5. Verification requires careful comparison with real cases, and/or subjective evaluation by domain experts.
Integrated DES and visualization with animation/ CAD/VR ***without*** **user interaction**	As above, and: 1. Verification is improved. 2. Simulations can use more complex data, including spatially-dependent data.	As above
Integrated DES and visualization with VR ***with*** **user interaction**	1. Experimenter has complete control of all of the experimental parameters. 2. Data collection is reliable, continuous and accurate. 3. The net impact of the innovation can be measured precisely. 4. The systems can be calibrated as needed. 5. Subjects can be de-briefed to learn about their motivations, their interactions with or attitudes to the intervention. 6. Subjects responses to unexpected events or unstructured problems can be explored.	1. The number of experimental runs is limited by the need to recruit and employ human subjects and the time required for each experiment. 2. Extensive resources are required for creating the virtual environments and for programming the interfaces.

3. VIRTUAL CONSTRUCTION SITE

In this section, we present a case study of a 'Virtual Construction Site' (VCS) setup, which was first designed and implemented to perform a series of laboratory experiments to test the field interfaces of the 'KanBIM' production control system for construction (Sacks et al., 2010). KanBIM is a prototype building information modeling (BIM) enabled software application designed to support Last Planner System (LPS) production planning and control. Its user-interfaces for the field provide real-time information on the construction process and enable collection of process status data from its users.

3.1 Experimental Setup

The goal for the laboratory experiments was to test the KanBIM prototype with live subjects in an environment that mimics construction site conditions with sufficient realism and freedom of action to study managerial decision making in context. Given the disadvantages of field tests outlined in Table 1, a second requirement for the setup was that it should enable the researchers to control the parameters affecting the performance sufficiently so that clear connections could be drawn between the decisions made and the operational outcomes. The solution proposed was to develop a hybrid system in which construction crew leaders could participate directly in discrete event simulation experiments, with their roles mediated using a virtual reality (VR) representation of the project, and in which they would be able to use the KanBIM system. Thus the integrated experimental system had to include direct two-way access for the KanBIM prototype to the DES in real-time.

In the experimental work scenario, the subject's goal was to build drywall partitions and to deliver maximum ready apartments in the shortest time possible. The subjects were given a set of plans defining the partitions to be built. Some of the partitions had electric conduits and piping, where the partitions had to be left with one side uncovered until the electrical and plumbing crews completed their installations. If their work was incomplete or if they had 'closed' partitions that were required to be left 'open', the plumber or electrician would not perform their work until the subject returned to the apartment and made corrections. Finally, they had to return to each apartment to close out the partitions, simulating a re-entrant workflow (Brodetskaia et al., 2011).

An important aspect of the construction context is that the actual conditions that develop on site cannot be predicted reliably by the planning function, with the result that even tasks that have been filtered for maturity in the planning process may turn out to be impossible to execute exactly as planned. For example, a crew may arrive at the work face and discover that the crew preceding them has not completed its work, or that they have not removed all of their equipment, or that the designs have changed, or the space is being used for temporary storage. The subjects made their decisions based on the information they could get from the working environment and/or from the KanBIM interface. Their actions were monitored and it is these decisions and the resulting workflows that were the focus for the data analysis.

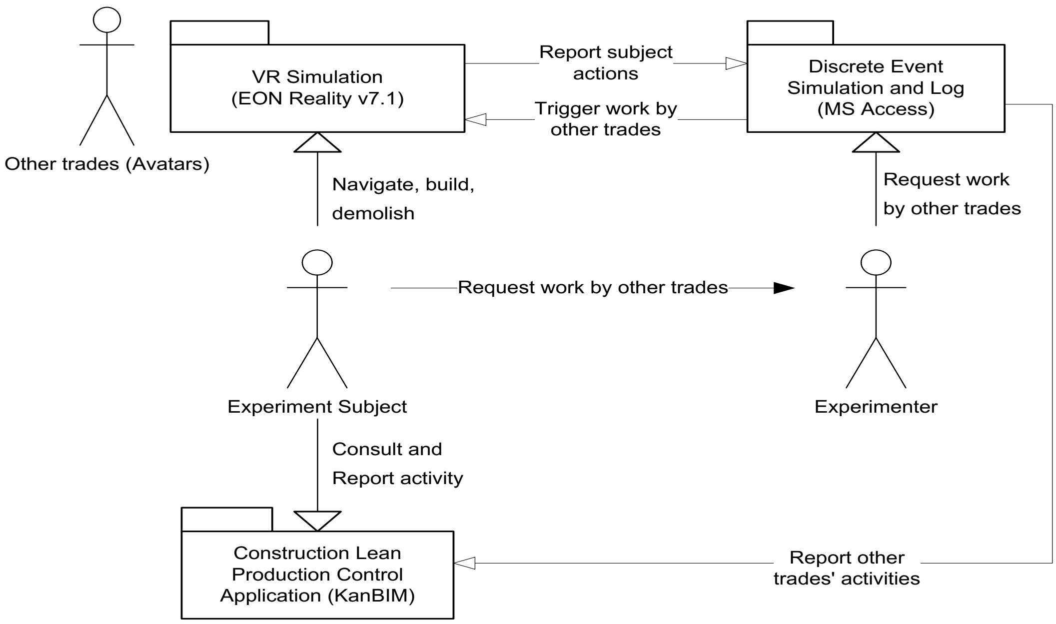


Fig. 1: UML use case diagram of the Virtual Construction Site experimental setup (Sacks et al., 2012).

The VCS was set up using a virtual reality CAVE (Cave Automated Virtual Environment). The virtual site model represented four stories of a residential building with four apartments per floor. A digital model was built using Autodesk REVIT, prepared using 3D Studio, and displayed using EON Studio in a three-sided EON Icube CAVE. The process aspect of the VCS was provided using a purpose-built discrete event simulation engine which was linked to the KanBIM application through an SQL database. Fig. 1 shows a UML use-case scenario of the experimental setup as a whole. The two human actors in the figure are the experimental subject, who fulfils the role of a single construction trade crew, and the experimenter. Workers of two other construction trades – electrical and plumbing crews – are visualized as avatars. The use case represents the experimental situation for testing the subject's behaviour while using the prototype. In the alternative baseline use case, the KanBIM production control application is removed and the subject gathers status information by navigating the building and observing the status of the work of the other trades.

In the VCS, subjects navigated the building and built the drywall partitions in each of the 16 apartments in the building. They used a remote control device to activate markings on the floor to consecutively build partition stud framework, cover one side with boards, and then cover the second side with boards, as shown in Fig. 2. Each step could also be undone to simulate demolition of work where necessary. In the course of the work subjects were required to report completion of stages of work to the supervisor (the investigator) so that other subcontractors (in this case an electrical and a plumbing crew represented by avatars) could install their system components inside the partitions. Subjects were required to return to complete the second side of each partition once the system installations are complete. Uncertainty was introduced by randomly applying obstacles to drywall installation in certain apartments, such as materials stored in an apartment that obstructs work, or scaffolding left by other trades, or introducing late design changes. The time, nature and location of the subjects' actions were recorded throughout the experimental runs.

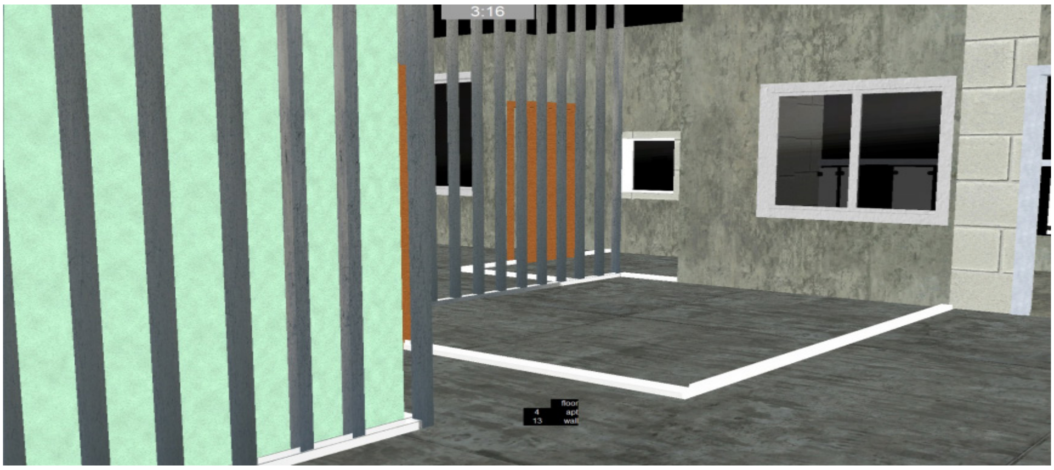


Fig. 2: Interior view of a virtual apartment, showing markings on the floor (at right), built studs (center) and studs with one side of boards built (at left).

3.2 Typical Results

The series of experiments conducted with the KanBIM prototype illustrate the nature of the results that can be achieved using the VCS setup. Each observation started with an introduction of the subject to the virtual construction project, their role in it as crew leader for the drywall team, the ways in which their work would be measured, and where necessary, the function of the KanBIM interface. Before starting the experiment itself, they were given 10-15 minutes to try the system, build partitions, and generally familiarize themselves with the environment. Each subject then worked in the VCS for one hour. All of their actions were logged and their locations were recorded every minute.

Fig. 3 shows an example of an 'as-performed' location-based progress charts for a single subject. Progress lines, such as the line marked 'a', represent where and when the subject worked. The lines marked 'b' and 'c' represent the electrical and plumbing crew avatars' work respectively. Following the lines from location to location indicates the crews' paths through the building, but viewing along a location also reveals the workflow in that location. Consider apartment #31: the subject began working in this apartment 225 work hours after the start (measured in simulation time). On completion, he informed the electrical crew, who in turn informed the plumbing crew when his work was complete. However, the plumbing crew identified an error, and notified the subject via the KanBIM interface. Only once the subject returned to the apartment and corrected the mistake (at hour 270) could the plumbing crew return to complete their work. The apartment was then unoccupied for a long period, until the subject returned to apartment #31 for the third time to close the drywalls (from 370 to 375 hours).

Despite the fact that none of the subjects had prior experience using a CAVE, in de-briefing they all reported that it represented the work environment sufficiently authentically that their behaviour was similar to what it would be on site. The following are comments written by three different subjects, describing aspects of their experience:

"I liked the idea of working on the virtual site. Although it doesn't really simulate the reality, it gives a feeling that you really work in a construction site. It can be used to investigate something very specific, but it would be very difficult to work on a virtual site if it worked exactly like a regular site."

"The construction site is a dynamic place, but not as dynamic as the virtual site. I felt that there were a lot of changes all the time."

"The experiment gave me the feeling that I'm in a construction site, although it does not really simulate the reality. In this experiment there are only two contractors, much less than in the construction site. The construction site is not as dynamic as the experiment. I worked in many apartments, did a lot of work and there where changes all the time, in the construction site the changes do not develop so fast."

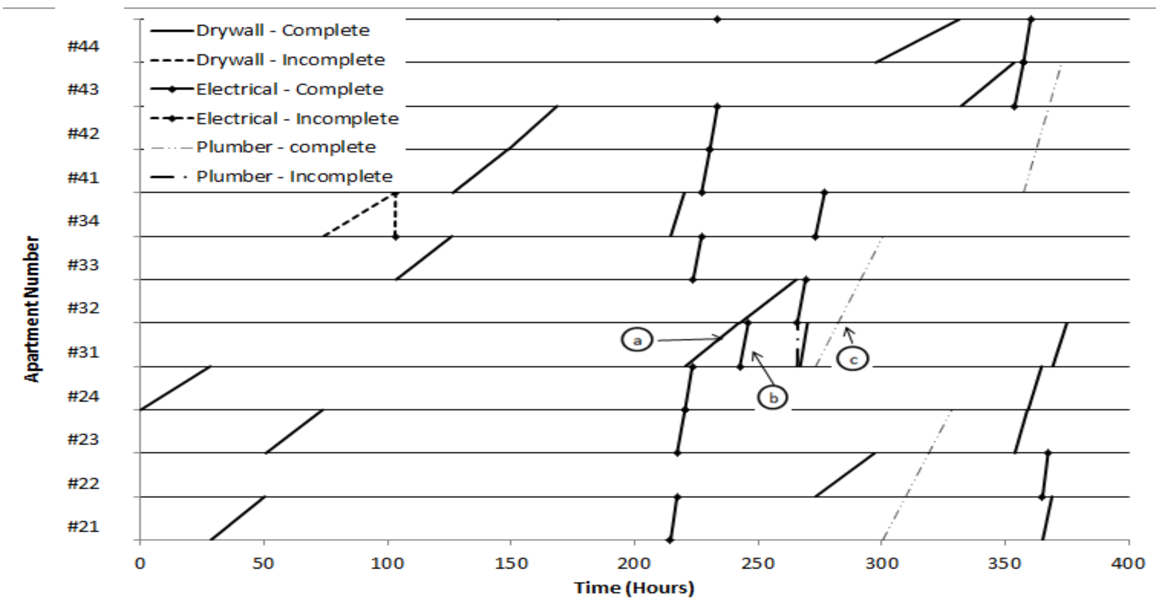


Fig. 3: Location-based progress chart for one experimental subject working without the KanBIM system

The subjects clearly felt the accelerated pace of events, which is due to the fact that actual production times (the time needed to build a partition's stud framing, for example) are collapsed in the VCS into the time of a single click of a button. The result is a sense of the intensity of decision-making in a short time. This also reflects the advantage of the VCS in that it allows researchers to observe far more decision events in a given time than they could during observations in the field.

During the first 20 minutes of each run (the first third) all subjects reported feeling curious and interested. During the second 20 minutes, those working without the KanBIM system reported feeling frustrated and confused as to what work remained to be done, while those using the system reported satisfaction, understanding and trust of the data presented. However, all subjects reported feeling impatience, irritability and fatigue during the last 20 minutes. One hour appears to be the maximum time that subjects can be asked to perform within the VCS setup, partly due to the discomfort of navigation in the 3D environment.

In addition to the location and performance data recorded in the experimental log, the integrated setup provided the opportunity to observe and feel the subject's decision making process in a live mode. The number of situations with which the subject could be confronted during one experimental hour, and hence the number of decisions that were taken and observed, was far greater than could be expected in field tests.

4. CONCLUSIONS

Various methods have been used for production system research in construction management. The most prominent methods are: field studies, case studies, and experimental methods. Experimental methods include role-playing simulations, discrete event simulations and the use of integrated systems such as DES with VR.

Field studies allow the researcher to observe subjects' behaviour directly, within the work environment. However, the intervention must be implemented, data collection may require frequent and intensive observations, and the duration of measurement needed is often long. Case studies are quite different. They report the results of the interventions that have been implemented in a project over some time (again, usually a long period), and they cannot test alternative processes. Their analysis is problematic because it is difficult to categorically associate causes with effects. Role-playing simulations have the advantage of engaging human subjects so that unpredicted or unexpected behaviours can emerge, but they are uncommon in research. The main drawbacks of this method are the influence of the researcher on the subject, the limited number of replications that can be done, and the potential for the subject to misinterpret the rules of their role. Discrete event simulations offer an entirely different method to the previous ones. It affords complete control of all of the experimental parameters and the short period of time required for each run allows many replications. The data collection is reliable, accurate and cheap and the net impact of the innovation can be measured precisely. The main problem of this method is that the behaviours of the actors in the process must be pre-programmed. Integrated systems are similar to the DES, but they are more sophisticated in that they enable experimentation with human subjects in a carefully controlled environment. They allow complete control of all the experimental parameters and offer reliable data collection. The opportunity to observe the simulation continuously allows the researcher to see how the subjects respond to unexpected events. The main drawback of this method, compared to DES, is the limited number of experimental runs that can be performed, which is due to the relatively long time needed to perform each run and to the need to employ professional subjects.

The VCS is an integrated experimental system. It extends earlier work in which human subjects interact with the virtual construction site by adding the ability to test the use of new information technology applications that communicate directly with the other actors and systems modelled in the discrete event simulation and the VR environment. The deleterious effects of 'noise' are eliminated, so that experiments can be repeated and results can be compared. The large setup cost for the VCS (modelling of the virtual environment, programming the DES, interfacing the production control system with the simulation, and programming the data collection) is offset by the quality of results that can be achieved. In the case study described in section 3 above, the VCS proved its efficacy by allowing the researchers to observe, record and analyse the decision-making behaviour of the human subjects in a controlled environment, with high accuracy and in relatively very short times.

Given the advantages and disadvantages of each method, researchers can select an appropriate method for testing production systems in accordance with the stage and scope of their project. For example, at the earliest stages of design and development of a production planning and control system, focus groups and/or in-depth interviews might be useful for collecting requirements or testing the attitudes of the target user group. Once a prototypical system has been implemented, use of an integrated DES and VR system seems appropriate. Field tests are only recommended when a more mature prototype is available. These three steps – design, analysis and testing of prototypes, and finally field trials – are common in other domains as well (such as product design). At the detailed design stage, computer environments and simulations allow the researcher to analyse, test and calibrate the systems as much as needed and with short cycle times, until it is ready for production.

5. REFERENCES

Abourizk, S. & Mather, K. 2000. Simplifying Simulation Modeling through Integration With 3D CAD. *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT,* 126**,** 475-483.

Ballard, G. 2000. *The Last Planner™ System of Production Control.* PhD Dissertation, The University of Birmingham.

Bell, P. C. & O'keefe, R. M. 1986. Visual Interactive Simulation: History, Recent Developments, and Major Issues. Blacksburg, VA: Virginia Polytechnic Institute and State University.

Brodetskaia, I., Sacks, R. & Shapira, A. 2011. Stabilizing Production Flow of Finishing Works in Building Construction with Re-entrant Flow. *Journal of Construction Engineering and Management,* under review.

Chen, Z., Li, H. & Wong, C. T. C. 2002. An application of bar-code system for reducing construction wastes. *Automation in Construction,* 11**,** 521-533.

Cmb 2010. Sim Lean. Stockholm: Chalmer's University.

Ergen, E., Akinci, B. & Sacks, R. 2007. Tracking and locating components in a precast storage yard utilizing radio frequency identification technology and GPS. *Automation in Construction,16***,** 354–367.

Farrar, J. M., Abourizk, S. M. & Mao, X. 2004. Generic Implementation of Lean Concepts in Simulation Models. *Lean Construction Journal,* 1**,** 1-23.

Halpin, D. W. 1977. CYCLONE - Method for Modeling Job Site Processes. *Journal of Construction Engineering and Management,* 103**,** 489-499.

Kamat, V. R. 2003. *VITASCOPE: Extensible and scalable 3D visualization*

of simulated construction operations. Ph.D., Virginia Polytechnic Institute and State Univ.

Kenley, R. & Seppänen, O. 2009. *Location-Based Management for Construction: Planning, Scheduling and Control* Spon Press.

Khanzode, A., Fischer, M. & Reed, D. 2005. Case Study of the Implementation of the Lean Project Delivery System (LPDS) using Virtual Building Technologies on a Large Healthcare Project. *In:* KENLEY, R. (ed.) *13th Conference of the International Group for Lean Construction.* Sydney, Australia: UNSW.

Koskela, L., Sacks, R. & Rooke, J. 2012. A brief history of the concept waste in production. *In:* TOMMELEIN, I. & PASQUIRE, C. (eds.) *Proceedings of the 20th Annual Conference of the International Group for Lean Construction.* San Diego, CA: San Diego State University.

Martinez, J. C. 1996. *STROBOSCOPE: State and Resource Based Simulation of Construction Processes.* PhD, University of Michigan.

Martinez, J. C. & Ioannou, P. G. 1999. General Purpose Systems for Effective Construction Simulation. *Journal of Construction Engineering and Management, ASCE,* 125**,** 265-276.

Merit 2012. MERIT Game. Loughborough: Construction Industry Simulations Ltd.

Ourplan. 2013. *The visual planning tool for lean construction* [Online]. Available: http://www.our-plan.com/ 2013].

Pheng, L. S. & Hui, M. S. 1999. The application of JIT philosophy to construction: a case study in site layout. *Construction Management and Economics,* 17**,** 657- 668.

Rekapalli, P. & Martinez, J. 2009. Runtime User Interaction in Concurrent Simulation-Animations of Construction Operations. *Journal of Computing in Civil Engineering,* 23**,** 372-383.

Ruwanpura, J. Y., Hewage, K. N. & Silva, L. P. 2012. Evolution of the i-Booth© onsite information management kiosk. *Automation in Construction,* 21**,** 52-63.

Sacks, R., Esquenazi, A. & Goldin, M. 2007. LEAPCON: Simulation of Lean Construction of High-Rise Apartment Buildings. *Journal of Construction Engineering and Management,* 133**,** 529-539.

Sacks, R., Gurevich, U. & Belaciano, B. 2012. A Hybrid Discrete Event Simulation and Virtual Reality Experimental Setup for Construction Management Research. *Journal of Computing in Civil Engineering,* (under review).

Sacks, R., Radosavljevic, M. & Barak, R. 2010. Requirements for building information modeling based lean production management systems for construction. *Automation in Construction,* 19**,** 641-655.

Seppänen, O. 2009. *Empirical Research on the Success of Production Control in Building Construction Projects.* PhD PhD, Helsinki University of Technology

Shtub, A. 2012. *Project Management Simulation with PTB Project Team Builder*, Springer.

Teizer, J. 2008. 3D RANGE IMAGING CAMERA SENSING FOR ACTIVE SAFETY IN CONSTRUCTION *ITcon - IT in Construction,* 13**,** 103-117.

Tommelein, I. D. 1998. Pull-Driven Scheduling for Pipe-Spool Installation: Simulation of Lean Construction Technique. *Journal of Construction Engineering and Management,* 124**,** 279-288.

Tommelein, I. D., Riley, D. R. & Howell, G. A. 1999. Parade Game: Impact of Work Flow Variability on Trade Performance. *Journal of Construction Engineering and Management,* 125**,** 304-310.

Walsh, K. D., Hershauer, J. C., Tommelein, I. D. & Walsh, T. A. 2004. Strategic Positioning of Inventory to Match Demand in a Capital Projects Supply Chain. *Journal of Construction Engineering and Management,* 130**,** 818-826.

Xue, X., Shen, Q., Fan, H., Li, H. & Fan, S. 2012. IT supported collaborative work in A/E/C projects: A ten-year review. *Automation in Construction,* 21**,** 1-9.

VAO CHECKER: ACCESSIBILITY STUDY FOR PIPELINE MAINTENANCE

Chu-Hsuan Lee, Meng-Han Tsai & Shih-Chung Kang
Department of Civil Engineering, National Taiwan University, Taiwan

ABSTRACT: *Pipeline maintenance is becoming an important issue in modern construction. An understanding of accessibility considerations in terms of operation and maintenance is essential for pipeline planning and management. Previous studies have highlighted the complexity of multi-pipes and the importance of visualization, but few have proposed a way to consider accessibility problems during operation and maintenance. Therefore, this study develops a systematic method to evaluate accessibility with respect to pipeline maintenance. We first divided pipeline accessibility into three categories: (1) visual accessibility—a pipeline visible to the inspectors; (2) approachable accessibility—a pipeline that is reachable; and (3) operational accessibility—a pipeline that can be operated by the inspectors. Therefore, we visually represent the intersection and union of these three levels to illustrate the varying accessibility of pipe elements. We then developed a user interface tool, VAO Checker, in which V, A and O stand for visual, approachable and operational, to display visual information about pipeline accessibility. Through instantaneous analysis, the system visualizes the accessibility of the pipelines. A usability consultation with experts will be conducted to validate the system's effectiveness. The results of the usability analysis show pipeline designers can benefit by using this tool to sketch a suitable traffic flow for engineers to investigate. Furthermore, the substantial amount of information saved in the layout database could be referenced for future optimization.*

KEYWORDS: *Building Information Model (BIM), Mechanical, Electrical, and Plumbing (MEP), Pipeline Maintenance, Pipeline Accessibility, Information Visualization*

1. INTRODUCTION

Pipeline design has become increasingly important in modern construction. Operation and maintenance requires consideration of accessibility in the design of the layout of plant pipelines. Previous research has noted that piping accounts for 20% of costs for the industry as a whole (Calixto et al., 2009) and over 50% of the total detail-design labor hours (Park and Storch, 2002). All other activities of following detail design depend on piping and massive savings are achievable by utilizing good layout design and engineering practices.

Mechanical, electrical, and plumbing (MEP) pipes used to be supplemental facilities in construction. However, they have become necessary facilities, especially in nonresidential construction, such as hospitals, fire stations, and plants. Coordinating a MEP system is a tremendous challenge in engineering fields such as advanced technology, health care, and biochemistry industries (Khanzode et al., 2008). Knowing how to arrange MEP systems appropriately is one of the most crucial aspects of the design phase (Riley et al., 2005).

Maintenance is a crucial phase in these types of construction. A poorly designed pipeline layout design wastes space and materials. Moreover, it can cause difficulty or even danger during manipulation and management.

2. LITERATURE REVIEW

The literature reviewed for this study included findings and recommendations related to piping that can be categorized into three main groups: a pipe-routing algorithm, the integration of multi-pipes, and the visualization of pipeline design.

2.1 Pipe-Routing Algorithms

Pipe-routing design is a subset of assembly design that conceives collision-free routes for pipes. A survey by Qian et al. (2008) categorized it into four fields: industrial plant pipeline layout design, circuit layout design,

Citation: Lee, C-. H., Tsai, M-. H. & Kang, S-. C. (2013). VAO checker: accessibility study for pipeline maintenance. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

aircraft design, and ship piping system design. Several studies have been devoted to routing algorithms, and mainly focus on physical constraints that connect the terminals of given locations and avoid all obstacles. They then use economic constraints to minimize the length of pipes and the number of pipe turns, which leads to an optimal specification. However, few, if any, solutions have considered pipeline accessibility in relation to operation and maintenance. Zhou and Yin (2010) emphasized that practical constraints, such as maintenance requirements and manufacturability, are not well recognized, and how humans still play an important role in guiding the computer to finish the design.

2.2 Integration of Multi-Pipes

An industrial plant typically has more than one kind of pipeline. Feng et al. (2012) indicated a large number of pipelines, multifarious design constraints, and numerous obstacles in layout complicates the design of a pipeline system. Recently, engineers have mainly used existing CAD software for design assistance, which has increased the problems associated with experts, such as complex operation, a long design cycle, and low efficiency. Feng *et al.* advocated a new layout space model to reduce high complexity and design interference in the automated design of pipeline systems. Kim et al. (1996) found the range and complexity of the constraints limits the possibility of automatic pipe route design, and demonstrated a more natural and effective representation for route optimization. The research of Kim *et al.* recognized the complexity in pipeline arrangement and proposed some methods to reduce it. However, in many instances the pipeline layout cannot be simplified, so the complexity should be taken into account.

2.3 Visualization Regarding Pipeline Accessibility

Some researchers have begun noticing the utility of information visualization for construction purposes as a means of improving the data-rich, but information-poor, problems of the construction industry (Kuo et al., 2011; Songer et al., 2004). Korde et al. (2005) and Russell et al. (2009) focused on the visualization of construction data, noting how it can help identify potential causal relationships among construction data. Gao et al. (2006) investigated colored construction drawing, which can increase the efficiency and accuracy of communication between designers and contractors. Chang et al. (2009) and Ya-Hsin et al. (2013) suggested a systematic procedure to determine the most suitable colors for effectively presenting the construction information. This procedure includes the selection, evaluation, and testing of colors to ensure they match the meaning of the construction information with the cognition of the users. With reference to pipeline arrangement, Deliang and Huibiao (2009) pointed out that visualization can help handle the detection and response to collisions between pipes and obstacles.

3. NEEDS ANALYSIS

We interviewed six experts in the field of plant pipeline design, including three engineers from a construction company, two managers from a microelectronics corporation, and one executive officer from the Building Information Modeling (BIM) research center.

We determined from the interviews that there are four main considerations in pipeline design: (1) the manufacturing process, (2) operation and maintenance, (3) cost, and (4) aesthetics. In a typical plant engine room, the engineers first have to deliberate how the pipelines go according to the manufacturing process, which will influence productivity and efficiency. They then contemplate how the workers will handle the equipment, meters, and valves during the operation and maintenance phase. Cost and aesthetics are aspects used to optimize the consequences of designs. Previous studies have proposed many algorithms by considering the cost factor, but maintenance is rarely discussed.

We mainly focused on operation and maintenance. Pipeline accessibility is the key factor to effective maintenance as it determines how easily the engineers can stretch to the accessories related to pipelines, including equipment, meters, and valves. Engineers can sometimes see pipelines from a distance, but cannot approach them due to the obstacles in the way of the pipelines. In other cases, engineers cannot read the meters in detail or operate the valves without difficulty, because these parts are mounted too high. We seek an easy way to illustrate pipeline accessibility with a view to engineers benefiting from this intuitive tool during the construction cycle (i.e., design, operation, and maintenance).

4. OBJECTIVE AND SCOPE

The aim of this study is to develop a systematic method to assist decisions about pipeline maintenance. One major challenge of coordinating MEP multi-pipes is identifying the spatial conflicts between systems. Through instantaneous analysis, the system automatically produces visual information indicating how much pipe access the engineers can have. This tool allows users to view, explore, and interact with the pipeline information via a direct manipulation interface in order to identify the spatial accessibility in a more intuitive manner. The user can thus obtain a comprehensive understanding of pipeline maintenance.

5. METHODOLOGY

We use a Venn diagram, a diagram that shows all possible logical relations between different sets, to differentiate three categories of pipeline accessibility. We then apply each section of the diagram to different scenarios. We further develop mathematical models and discuss the ergonomic details about each different category.

5.1 Overall Procedure of Pipeline Accessibility

We proposed three categories, *visual*, *approachable*, and *operational* to present the extent to which the pipe elements are accessible. As shown in Fig. 1, we use the intersection and union of these three categories to discuss different scenarios as follows:

Visual (V): determines how much of the pipe is directly visible for inspection.

Approachable (A): determines how far maintenance engineers can walk along the pipes.

Operational (O): checks how much of the pipes can be reached in order to operate valves or check surfaces.

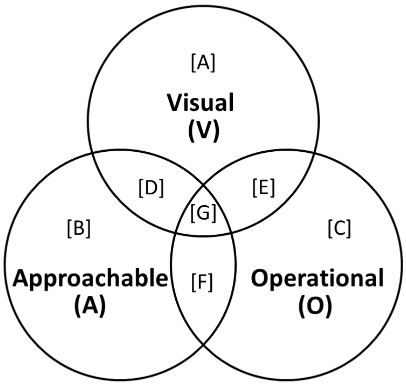


Fig. 1: Venn diagram of pipeline accessibility

In the Venn diagram, there are seven sections among the three circles. Each one is a variation of intersection and union. As listed in Table 1, we give the accessibility description of each variation from Fig. 1.

Table 1: Seven variations of intersection and union

Section	Math Representation	Accessibility Description
[A]	$V - A - O$	Only visible, but not approachable and operable. This happens when obstacles and other pipes prevent engineers from accessing equipment and pipelines.
[B]	$A - V - O$	Only approachable, but not visible and operable. This happens when obstacles and other pipes block displays and controls.
[C]	$O - V - A$	Only operable, but not visible and approachable. Although remote control is possible, we did not consider this variation.
[D]	$V \cap A - O$	Visible and approachable, but not operable. This happens when controls or valves are mounted too high, too low, or too far away to reach and operate.

[E]	$V \cap O - A$	Operable and visible, but not approachable. The same as [C]. We did not consider this variation.
[F]	$A \cap O - V$	Approachable and operable, but not visible. This happens when controls and valves are mounted behind the display, and engineers have to bend their arms to operate them. However, any blindness operation is not allowed in our assumption.
[G]	$V \cap A \cap O$	Visible, approachable, and operable—the ideal situation.

These three categories are expressed in a visual conception of information. We adopted the anthropometric data from the American Bureau of Shipping (ABS, 2003) to build the model for accessibility analysis. We made some modifications by considering the physical differences between Americans and Taiwanese, because the first case would be a semiconductor fabrication plant in Taiwan.

5.2 Approachable Accessibility

This level determines how far people can walk along the pipes. Walkways should have 2.1 m minimum clearance above the walking surface for the full length and width of the walkway. The analysis and mathematical model of approachable accessibility is different from the other two because it is a dynamic process. As shown in Fig. 2 and Table 2, we first use a bounding cylinder to represent a person, and bounding boxes in different sizes to represent a cart in different applications. If obstacles or other pipes block the box, it cannot go farther along the pipes.

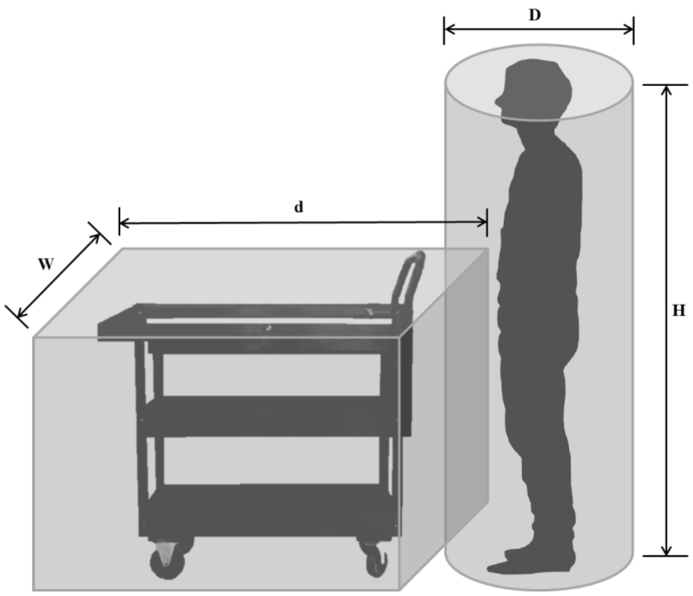


Fig. 2: Bounding cylinder and box representation

Table 2: Bounding box size for recommended walkway dimensions

Application	Box size *
One person traveling in an area with limited access	51×51×150
One person in unrestricted area, where two persons could pass	71×71×210
One person with a cart	71×120×210
Normal two-way traffic or any means of egress that leads to an entrance or exit	92×120×210
Corridor or passageway that serves as a required exit	112×120×210

* Size representation: W (cm) × (D+d) (cm) × H (cm)

The mathematical model of visual accessibility is then constructed as the equation:

$$A = (H, r, P) \tag{1}$$

As denoted in Fig. 3, $r = \frac{Max(W,D)}{2}$, and we used a cylinder with radius r and height H to simplify the bounding box. S means the start point, and T means the target point. P is the path from S to T:

$P = [S, p_1, p_2, \dots, p_n, p_{n+1}, \dots T]$, where the cylinder is not blocked.

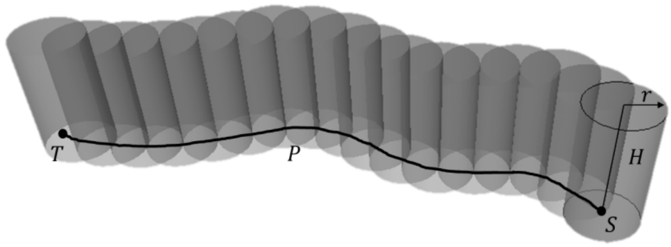


Fig. 3: Mathematical model of approachable accessibility

5.3 Visual Accessibility

This level determines how much of the pipe is directly visible for inspection. We further divide it into two levels: visible and legible. The former includes those used for normal operations and those not requiring accurate readings, whereas the latter includes those used frequently, for obtaining precise readings, and in emergencies. The mathematical model of visual accessibility is constructed as the following equation. Fig. 4 indicates the parameters.

$$V = \left(S,\ H,\ L_{min},\ L_{max}, \theta,\ H^{v}_{min}, H^{v}_{max}\right) \tag{2}$$

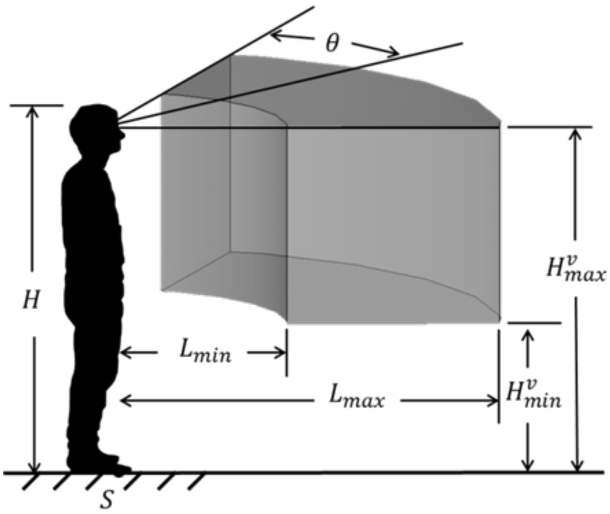


Fig. 4: Mathematical model of visual accessibility

Table 3: Suitable field-of-view and vision range (multiple of H) for legible and visible levels

Posture	L (cm)	θ (degrees)	Standing (C)	Kneeling (D)	Squatting (E)	Overall
Visible Maximum	200	60	1.0114	0.8239	0.7102	1.0114
Legible Maximum	71	35	0.9375	0.7500	0.5795	0.9375
Legible Minimum	33	0	0.7216	0.5398	0.4261	0.4261
Visible Minimum	0	0	0.5909	0.3977	0.2955	0.2955

The two parameters regarding people's field-of-view are the distance from eyes (L) and the viewing angle from the central line (θ). Based on ABS research, as shown in first two columns of Table 3, people can see the details of pipes at distances between 33cm and 71cm, and a viewing angle within 35 degrees, where the legible level should be located (provided obstacles or other pipes do not block the pipes and displays). The distance for the visible level can be up to 200cm, with the viewing angle up to 60 degrees. The visual heights (H^v) for displays in different postures are illustrated in Fig. 5: standing (C), kneeling (D), and squatting (E). The rest of Table 3 shows the maximum and minimum heights for the legible and visible levels, based on personal height (H). Because the range of these three postures overlapped, we integrated the data. The legible level should be located within the multiple 0.4261-0.9375, but the visible level can be broader, 0.2955-1.0114.

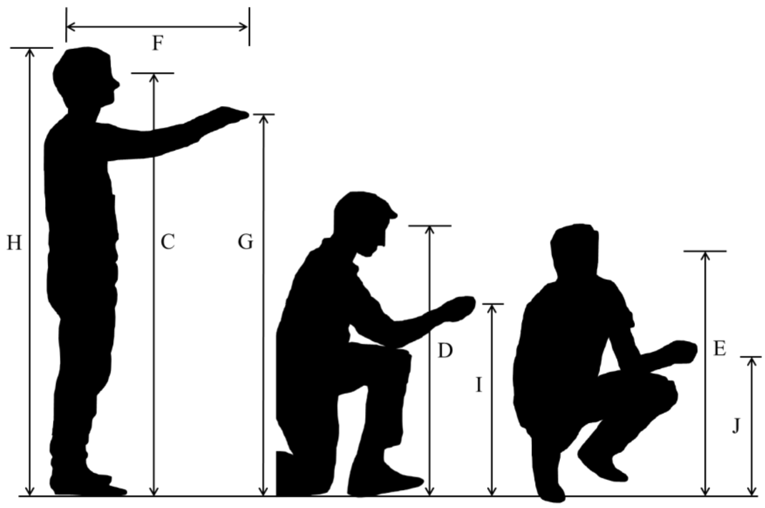


Fig. 5: Related height in different postures

5.4 Operational Accessibility

To facilitate the operation of valves or the checking of surfaces, this level checks the accessibility of pipes. It is derived from the arrival accessibility level, and shows the ease with which people can operate within the pipe layout. We further divided it into two levels: general control and precise control. The former includes those used for normal operations and those not requiring accurate manipulation, whereas the latter includes those used frequently, for obtaining precise performance, or in emergencies. The mathematical model of operational accessibility is constructed as the following equation. Fig. 6 indicates the parameters.

$$O = (S,\ H,\ F,\ H^{o}_{min}, H^{o}_{max}) \qquad (3)$$

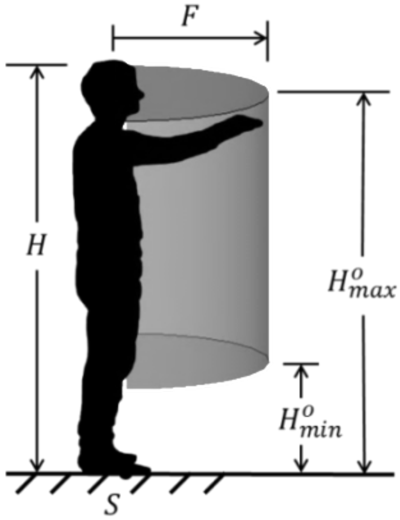


Fig. 6: Mathematical model of operational accessibility

People's forward functional reach from behind the shoulder to the tip of the extended finger (F) and the operable heights (H^{o}) for controls in different postures are illustrated in Fig. 5: standing (G), kneeling (I), and squatting (J). Table 4 shows the maximum and minimum forward functional reach and heights for precise and general controls, based on personal height (H). Frequently used controls should be located within a radius of multiple 0.2614 from the operator's centerline, whereas less frequently used controls should be located within a radius of multiple 0.4545 from the operator's centerline. Because the range of these three postures overlapped, we integrated the data. Precise control should be located within the multiple 0.2273-0.7670, but general control can be broader, 0.2045-1.0966.

Table 4: Suitable forward functional reach and heights (multiple of H) for precise and general controls

Posture	Forward (F)	Standing (G)	Kneeling (I)	Squatting (J)	Overall
General Maximum	0.4545	1.0966	0.8239	0.7102	1.0966
Precise Maximum	0.2614	0.7670	0.6136	0.4545	0.7670
Precise Minimum	0	0.4886	0.3068	0.2273	0.2273
General Minimum	0	0.4318	0.2614	0.2045	0.2045

6. IMPLEMENTATION

This study developed a system, VAO Checker, which integrated the user interface and visualization information as a tool, to implement the proposed methodology. The following sections describe the software used for the development environment and the system design.

Programming Platform: This study used Microsoft Windows Presentation Foundation (WPF) for the display of the user interface. WPF was chosen because it allows programmers to easily unify multimedia data, and change the appearance or the function of display controls for customization. Furthermore, the WPF application functions by off-loading to graphics processing units (GPUs) rather than central processing units (CPUs), which facilitates smoother graphics and better performance (Nathan, 2006).

Graphics Engine: The framework developed for the visualization information was based on the Microsoft XNA Game Studio 4.0. This tool assists the development of video games and the improvement of software management. XNA has ample performance for the development of 2D and 3D games. It offers users the capability to build the operating system and visual images with ease (Grootjans, 2009; Miller and Johnson, 2010).

System Design: The proposed tool called VAO Checker was built for this study to consider the three categories of pipeline accessibility. As shown in Fig., the operation interface displays a plan view of the space, including the equipment and pipelines. The user can use this tool to find a collision-free path through the space and to examine the different levels of visual and operational accessibility.

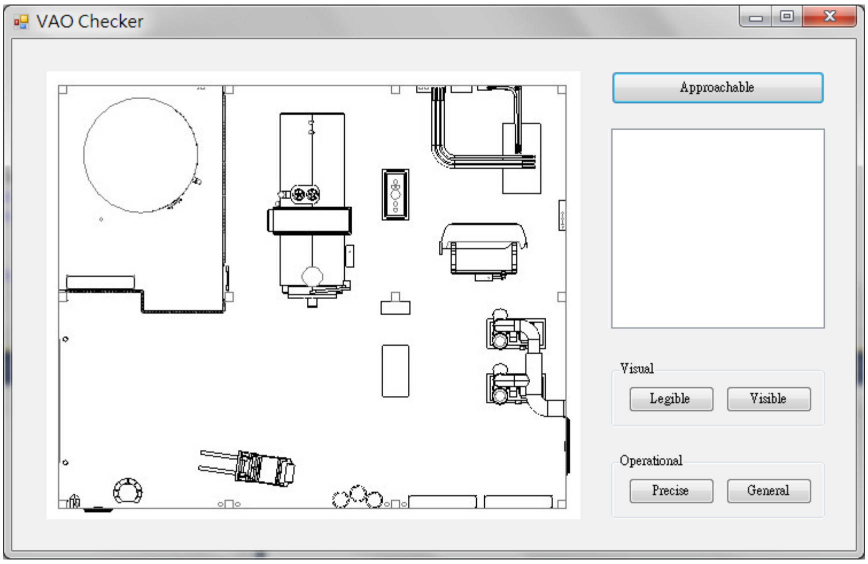


Fig. 7: Operation interface of VAO Checker

7. VALIDATION

In order to verify how VAO Checker could help users explore and understand relevant accessibility information, we conducted a usability test. We also solicited expert consultation to verify the usability and how the users can interact with the pipeline accessibility information.

7.1 Test Plan

For the usability test, we built a typical machinery room project with equipment and pipelines. There were 10 accessibility problems in this case. All users had to identify the problems in three individual tasks, each task using different mediums, 2D plan drawing, 3D model and our system, VAO Checker. Besides, we also conducted the NASA Task Load Index (NASA-TLX) test. As shown in Fig. 8, the test plan began with the NASA-TLX weight assessment, in which the user compared the factors pairwise based on their perceived importance. After the user finished the identification of accessibility problems via one information medium, the user had to rate each factor of task load within a 100-points range. The final NASA-TLX score was calculated based on the weight distribution, which was decided at the initial phase.

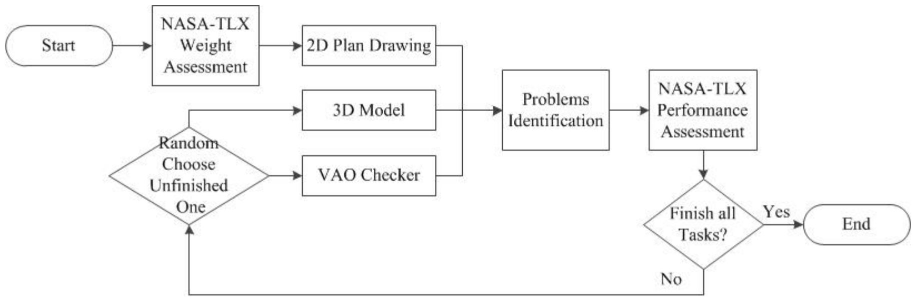


Fig. 8: Usability test procedure

7.2 Test Result

An α level of 0.05 was used for all statistical tests and analysis, and we calculated the p-value between groups in analysis of variance (ANOVA), where $p < 0.05$ means statistically significant. The test results assessed how quickly and accurately participants performed the task when using different mediums. There is also an analysis of NASA-TLX score, which shows how the participants evaluated the ergonomics performance of each medium. They are summarized as follows:

Correctness: VAO ≧ 3D > 2D

Table 5 presents means and standard deviations of success rate of each medium, and the p-value shows the data between 2D and VAO Checker is statistically significant. As the data indicates, the success rate of VAO Checker (64.3%) is 1.6 times higher than 2D plan drawing (40.1%) and 1.14 times higher than 3D model (56.4%).

Table 5: Statistical analysis of correctness

Medium	Mean (%)	Std. Deviation (%)	p-value (* means significant)	
2D plan drawing	40.1	16.3	2D & 3D	0.002*
3D model	56.4	25.3	2D & VAO	0.000*
VAO Checker	64.3	24.5	3D & VAO	0.139

Performance: 3D > VAO > 2D

Table 6 presents means and standard deviations of NASA-TLX score of each medium, and the p-value shows the data between each pair of these three groups is statistically significant. The score of 2D plan drawing is the lowest (36.0), whereas the score of 3D model is the highest (53.8). The score of VAO Checker (48.0) is 1.33 times higher than 2D plan drawing.

Table 6: Statistical analysis of performance

Medium	Mean (points)	Std. Deviation (points)	p-value (* means significant)	
2D plan drawing	36.0	13.5	2D & 3D	0.000*
3D model	53.8	17.0	2D & VAO	0.004*
VAO Checker	48.0	17.3	3D & VAO	0.020*

7.3 Discussion

Most of the participants have a background of civil engineering, and they can get on track quickly when they check 2D plan drawing or 3D model. Based on the observation during the usability test, participants would spend some time to get used to the user interface of VAO Checker, because it is a new tool for them. However, in the analysis of correctness, the success rate of VAO Checker is the highest. This means, although users might spend more time when they first contact with the user interface of VAO Checker, they still can achieve the goal of high correctness.

In the analysis of performance, the NASA-TLX score of VAO Checker is higher than 2D plan drawing, and 3D model is higher than VAO Checker. We also interviewed the participants about their feeling when they manipulated VAO Checker. Many of them pointed out that the manipulation of VAO Checker had a sense of reality, unlike 2D plan drawing. They could look around the environment, and perceive the size of equipment and pipelines. The visual effects made it like playing a game. However, due to the unfamiliarity with the overall pipeline design, they sometimes got confused with the direction in the virtual environment. That is the reason some participants evaluated the NASA-TLX score of 3D model higher.

Despite the participants needed some time to be familiar with the manipulation interface of VAO Checker, they all agreed that they could identify the accessibility problems very easily via this tool, because it provided sufficient information for them to judge the level of pipeline accessibility. They expected the path generated from analysis of approachable accessibility could be used for inspection or judgment, and the engineers would have a certain understanding of pipeline maintenance of the entire environment if they could move along this path.

VAO Checker would serve as a useful tool for the designers who are conscious of the design, and they would benefit from this tool to correct any design errors. Experts suggested that VAO Checker is suitable for planning a more complex environment, such as chiller machinery room. The sizes of pipelines are bigger, and there are more relevant systems. Formerly only experienced designers could plan a pipeline layout which is acceptable enough. Through VAO Checker, designers could save a lot of time in analyzing and planning.

8. CONCLUSION

This research developed a systematic method to evaluate the accessibility of pipeline maintenance. During the early stage of this research, we interviewed six experts to determine the requirements of pipeline design. After combining the opinion of experts with a literature review, we mainly focused our research on pipeline accessibility during operation and maintenance, which is rarely discussed in previous studies. We first divided pipeline accessibility into three categories, developed mathematical models, and discussed the ergonomic details of each different category. We then developed a system called VAO Checker, which integrated the user interface and visualization information as a tool to implement the proposed methodology. VAO Checker used a simple motion-planning algorithm to find a path with acceptable approachable accessibility, and programmed the mathematical models into visualization information indicating the visual and operational accessibility. We created an example case to validate the practicality of VAO Checker, and the result showed that it is a useful system for pipeline designers and engineers. It considered the pipeline accessibility within multi-pipes and enhanced the spatial comprehension. The system can be further integrated into BIM software as an API, extended to pipe assembly planning areas, or even referenced for future optimization.

9. ACKNOWLEDGEMENT

This research was supported in part by Taiwan's Ministry of Economic Affairs, under contract 101-EC-17-A-15-S1-223. The authors are grateful to Mr. Chien-Chih Lai of L&K Engineering CO., LTD., Mr. Ching-Yang Kao and Mr. Ming-Fa Lin of United Microelectronics Corporation (UMC), Mr. Yuan-Fu Liao and Mr. Yi-Ti Tsai of CTCI Corporation and Mr. Ching-Hsien Lee of Research Center for BIM, National Taiwan University for their kind support and assistance in this research. We like to express our appreciation to the interviewees of these corporations and organizations.

10. REFERENCES

The American Bureau of Shipping (ABS) (2003). *Guidance notes on the application of ergonomics to marine systems*, Houston, USA, American Bureau of Shipping.

Calixto E. E. S., Bordeira P. G., Calazans H. T., Tavares C. A. C. and Rodriguez M. T. D. (2009). Plant design project automation using an automatic pipe routing routine, *Computer Aided Chemical Engineering*, Vol. 27, 807-812.

Chang H. S., Kang S. C. and Chen P. H. (2009). Systematic procedure of determining an ideal color scheme on 4D models, *Advanced Engineering Informatics*, Vol. 23, 463-473.

Deliang L. and Huibiao L. (2009). Interfere-check applying to 3D automatic pipe route arrangement, *Proceedings of International Conference on Computational Intelligence and Software Engineering*, Wuhan, China, IEEE, 1-3.

Feng H., Fu Y. and Li L. (2012). Layout space modeling for automation design of pipeline system, *Proceedings of 2012 International Conference on Mechatronics and Automation (ICMA)*, Chengdu, China, IEEE, 881-886.

Gao Z., Walters R. C., Jaselskis E. J. and Wipf T. J. (2006). Approaches to improving the quality of construction drawings from owner's perspective, *Journal of construction engineering and management*, Vol. 132, 1187-1192.

Grootjans R. (2009). *XNA 3.0 Game Programming Recipes: A Problem-Solution Approach*, Apress.

Khanzode A., Fischer M. and Reed D. (2008). Benefits and lessons learned of implementing building virtual design and construction (VDC) technologies for coordination of mechanical, electrical, and plumbing (MEP) systems on a large healthcare project, *Journal of Information Technology in Construction*, Vol. 13, 324-342.

Kim D., Corne D. and Ross P. (1996). Industrial plant pipe-route optimisation with genetic algorithms, *Lecture Notes in Computer Science*, Vol. 1141, 1012-1021.

Korde T., Wang Y. and Russell A. (2005). Visualization of construction data, *Proceedings of 6th Construction Specialty Conference*, Toronto, Ontario, Canada, University of British Columbia.

Kuo C. H., Tsai M. H. and Kang S. C. (2011). A framework of information visualization for multi-system construction, *Automation in Construction*, Vol. 20, 247-262.

Miller T. and Johnson D. (2010). *XNA Game Studio 4.0 Programming: Developing for Windows Phone 7 and Xbox 360*, Addison-Wesley Professional.

Nathan A. (2006). *Windows presentation foundation unleashed*, Sams Publishing.

Park J. H. and Storch R. L. (2002). Pipe-routing algorithm development: case study of a ship engine room design, *Expert Systems with Applications*, Vol. 23, 299-309.

Qian X., Ren T. and Wang C. (2008). A survey of pipe routing design, *Proceedings of 2008 Chinese Control and Decision Conference*, Yantai, China, IEEE, 3994-3998.

Riley D. R., Varadan P., James J. S. and Thomas H. R. (2005). Benefit-cost metrics for design coordination of mechanical, electrical, and plumbing systems in multistory buildings, *Journal of construction engineering and management*, Vol. 131, 877-889.

Russell A. D., Chiu C. Y. and Korde T. (2009). Visual representation of construction management data, *Automation in Construction*, Vol. 18, 1045-1062.

Songer A. D., Hays B. and North C. (2004). Multidimensional visualization of project control data, *Construction Innovation: Information, Process, Management*, Vol. 4, 173-190.

Ya-Hsin C., Meng-Han T., Shih-Chung K. and Chin-Wei L. (2013). Selection and evaluation of color scheme for 4D construction models, *Journal of Information Technology in Construction*, Vol. 18, 1-19.

Zhou C. and Yin Y. H. (2010). Pipe assembly planning algorithm by imitating human imaginal thinking, *Assembly Automation*, Vol. 30, 66-74.

VISUALIZATION OF CROWD FLOW IN LARGE-SCALE FACILITY USING AGENT-BASED SIMULATION[1]

Kensuke Yasufuku
Osaka University, Japan

ABSTRACT: *To prevent crowd accidents in large-scale facilities that are available to the general public, it is important to share information on safety measures among organizers, the police, the fire department, and government officials. In this study, we present a crowd simulation system that is capable of sharing visual information on the estimated flow of the crowd and that can be used when the safety plan for a facility is being developed. The simulation is agent based and aims to reproduce the macroscopic phenomena of a crowd flow, especially in a queue, by modeling the microscopic interactions between the agents. This crowd behavior model is divided into three parts: route choice, crowd movement, and queue formation. Route choice is implemented using a simple graphical user interface (GUI); this enables the choice of an arbitrary route to guide each agent. Crowd movement is based on a social force model. In addition, we implement a queue formation model in which the route to a destination is changed according to the length of the queue in a specific area. The results are as follows. We calibrated the parameter of the simulation and reproduced the density of a crowd flow based on empirical observations. Queuing behavior was also verified for the emergence of the macroscopic phenomena of stop-and-go waves. Moreover, we applied this simulation to evaluate crowd safety for a special event held in a large-scale commercial facility. We propose a new method for safety experts and non-experts to share visual information about the flow of crowds.*

KEYWORDS: *Autonomous agents, crowd flow, visual simulation, large-scale facility*

1. INTRODUCTION

Safety measures to prevent crowd accidents have become increasingly important as the size of urban facilities and the frequency of mass events has increased. The incident on the Akashi pedestrian bridge that occurred on 21 July 2001 in Akashi, Hyogo, Japan killed 11 people and injured 247 people. This was due to the accumulation of the crowd on the pedestrian overpass that connects the site and the nearest railroad station. The resulting trial determined that the organizers of such an event were responsible for the safety of the crowd. Since that date, however, there have continued to be crowd accidents worldwide: the Baihe fireworks display disaster in China in 2004 (37 deaths, 37 injuries), the Duisburg Love Parade disaster in Germany in 2010 (37 deaths, over 500 injuries), and the Water Festival disaster in Cambodia in 2010 (348 deaths, over 600 injuries). An investigation pointed out that safety measures for high-density crowd flows were not always considered when planning mass events (Kaitsuji et al., 2010). To prevent crowd accidents in large-scale facilities that are available to the general public, it is important to share information on safety measures among organizers, the police, the fire department, and government officials.

To make an efficient plan for the prevention of crowd accidents, it is important to study past crowd accidents. Using individual trajectories to simulate crowds is an especially effective way to evaluate crowd flows and to share visual information. Many different models of human behavior have been proposed to reproduce the typical emergent phenomena of crowd flows in a simulation. Among these, agent-based approaches, which model the microscopic behaviors of individuals, are currently very common. Well-known examples are the social force models (Helbing et al., 2000), the cellular automaton models (Burstedde et al., 2001), and the rule-based models (Berg et al., 2008). Currently, one of the key areas for future research is simulating the behavior of groups. Lemercier et al. (2012) propose a realistic model of the following behavior in a queue by controlling the instantaneous tangential acceleration. However, the ability of this model to reproduce a high-density queue and dynamic queue formation have not yet been fully developed. Moreover, it has not been applied to a large-scale facility.

Citation: Yasufuku, K. (2013). Visualization of crowd flow in large-scale facility using agent-based simulation. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

This study develops an agent-based crowd simulation that reproduces the macroscopic phenomena of crowd flow, especially in the area of the queue in front of the entrance. Our simulation does this by modeling the microscopic interactions between agents. In addition, we apply this simulation to a large-scale facility that is currently under construction and provide visual information for the crowd flow that can be used when developing the safety plan for the facility.

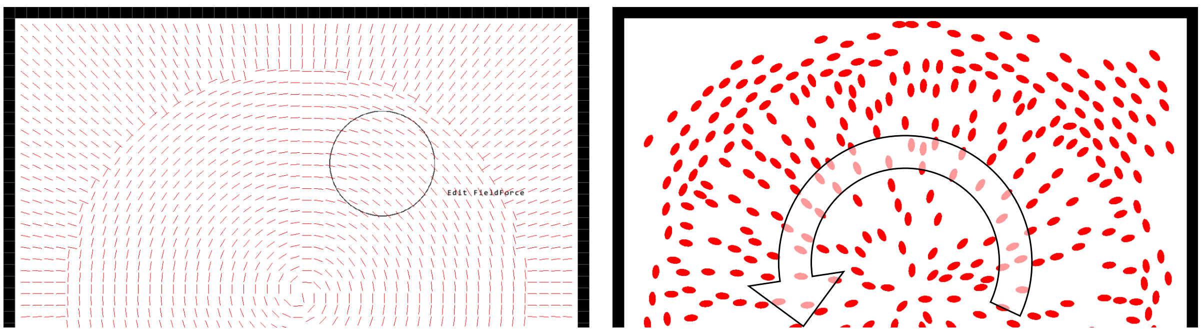
2. METHOD

2.1 Development of Agent-based Crowd Simulation

We developed an agent-based simulation to evaluate the flow of the crowd in an urban facility. To reproduce the macroscopic phenomena of the crowd flow, especially in a queue, we propose a behavior model that is based on the social force model (Helbing et al., 2000). Behavior consists of three submodels: (1) route choice: each agent setting a destination and calculating the route; (2) crowd movement: agents approaching the destination and avoiding collisions; this section takes the entry queue into account; (3) queue formation: agents forming a queue in a specific area.

2.1.1 Route-choice model

In the route choice model, each agent at each time step determines the direction vector towards the chosen destination. In this model, a plan of the target site or a floor plan is divided into a square grid and the direction vectors are set on each grid point, using a simple graphical user interface (GUI) route-editing tool (Fig.1). This tool enables us to set any direction for the vector at each grid point, just like painting. The direction vector at the grid point at which an agent stands is used for the next step of the route. The size of the grid is variable, but there are trade-offs between the accuracy of the plan and the calculation time. In this study, we set the grid size to 50 cm on a side in order to model individual agent in a large-scale facility.



setting the direction vector　　　　route choice

Fig. 1: Route choice based on direction vector and editing tool

2.1.2 Modeling the movement of a crowd in a queue

We used a social force model to approximate the microscopic movement behavior of a crowd. In the social force model, each agent is represented by a self-driven particle that is subject to both social and physical forces. Accordingly, agents i with a certain mass m_i like to move in a certain direction $\mathbf{e}_i^0$ at a certain speed v_i^0, adapting their velocity within a certain time period τ_i, while keeping their distance from other agents j and obstacles W. Therefore, the social forces consist of (1) an attracting force from a direction vector of the route choice model; (2) repulsive forces from other agents $\mathbf{f}_{ij}$; and (3) repulsive forces from walls and other obstacles $\mathbf{f}_{iW}$; as shown in Fig. 2. The mathematical representation of these forces is presented, in Eqs. 1. Each agent calculates the force and updates its walking speed once per time step. To restrict oscillation and numerical errors, a maximum walking speed is limited.

However, if we try to use the social force model to reproduce the behavior of a crowd in a queue, there are several issues. One is that the social force model cannot represent a high-density crowd in a queue because the shape of each agent is approximated by a circle. The other is that the social force model does not take into consideration the behavior of following in a queue. Because of this, we developed (1) ellipse-based collision detection and (2) velocity alignment parameters to model the following behavior in a queue, based on the social force model.

In the ellipse-based collision-detection process, the shape of each agent is approximated using an ellipse, and the collisions between them are detected. Specifically, the radius (r_i) of agent i is set the radius vector in the direction of the other agent j (see the right-hand side of Fig.2).

The velocity alignment parameter causes the velocity of each following agent to adapt to the velocity of the leading agent. If the distance between the following leading agents is less than D_i, the following agent is forced to adapt to the speed of the leading agent. If the distance is less than C_i, the following agent is forced to stop in order to avoid a collision (Eqs. 2).

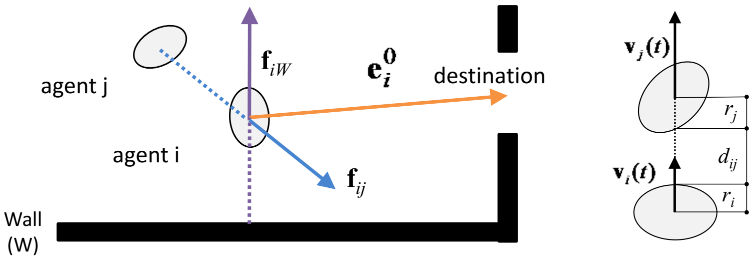


Fig. 2: Model of the social force between ellipses

$$m_i \frac{d\mathbf{v}_i}{dt} = m_i \frac{v_i^0(t)\mathbf{e}_i^0(t) - \mathbf{v}_i(t)}{\tau_i} + \sum_{j(\neq i)} \mathbf{f}_{ij} + \sum_W \mathbf{f}_{iW} \qquad (1)$$

$$v_i^0(t) \begin{cases} |\mathbf{v}_i(t)|s + |\mathbf{v}_j(t)|(1-s) & (C_i \le d_{ij} < D_i) \\ 0 & (d_{ij} < C_i) \end{cases} \qquad s \begin{cases} \left(1 - \dfrac{d_{ij} - C_i}{D_i - C_i}\right)^2 & (|\mathbf{v}_i(t)| \ge |\mathbf{v}_j(t)|) \\ 0 & (|\mathbf{v}_i(t)| < |\mathbf{v}_j(t)|) \end{cases} \qquad (2)$$

2.1.3 Queue formation model

The queue formation model represents the creation of a queue near an entrance to a facility. Specifically, each agent is given a direction vector based on if the agent is standing in a queue area, a detour area, or another area. A queue area is where the agents stand in a queue. A detour area is where agents take a roundabout route to go to the rear of a queue (note that the location of the detour area changes as the queue forms and develops).

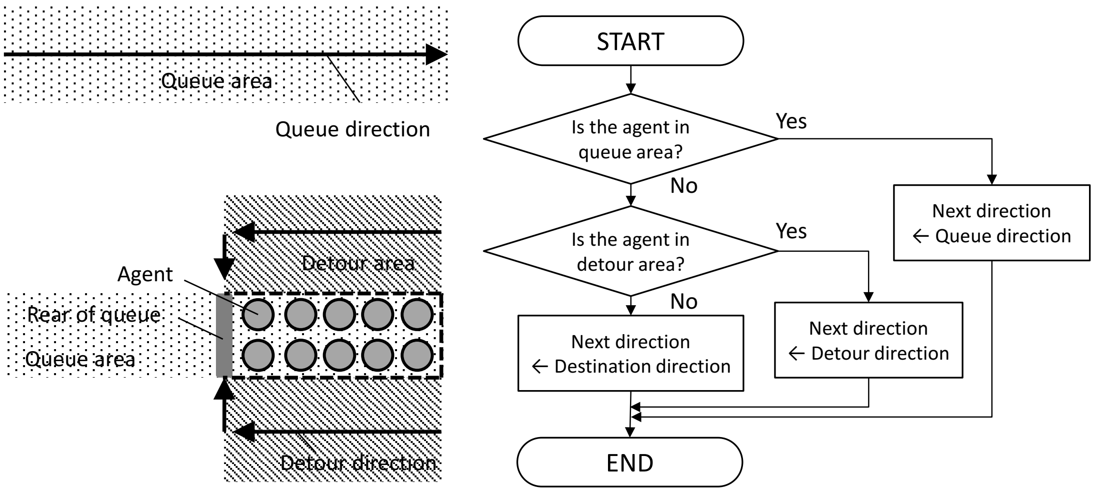


Fig. 3: Queue formation model

When an agent enters a queue area, the direction vector of the agent is set to the queue direction. This direction is distinguished from that of the route choice model. Figure 3 shows the directions in a queue area and a detour area. When an agent reaches the vicinity of a queue area, the agent tries to join the queue. However, if there is already a queue, the agent is directed to detour to the rear of the queue. A specific area around a queue and ahead of the rear of the queue is the detour area. If an agent reaches the end of the queue, the agent joins it. If a queue area is widened, a multi-line queue is formed by the action of force toward the queue direction and repulsive force from other agents. The agents in the queue are also made not to get out of the queue by repulsive force from the outside of a queue. The position of the rear of a queue moves in the direction opposite that of the queue if the density of the queue is greater than a specified value. The settings for the area and direction of the queue and the detour area can be changed by using an editing tool (Fig.4).

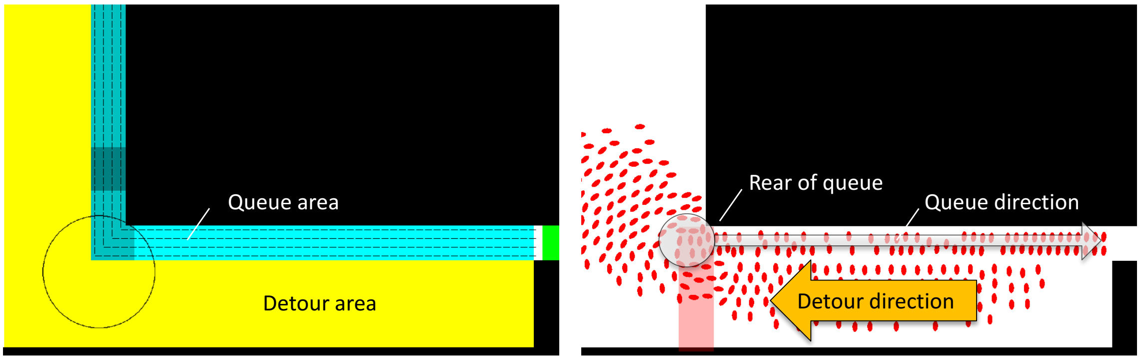


Fig. 4: Queue-editing tool

2.2 Verification of Crowd Behavior in Queues

To verify the reproducibility of crowd behavior in a queue by using our crowd simulation, we evaluated (1) the way in which the parameter choice changed the linear density, (2) how the simulated crowd flow compared with observation data, and (3) the way in which the process of formation of a queue depends on the shape of the queue area.

Specifically, we measured the changes in the linear density due to the size of the ellipse that represents the exclusive area of an agent, and compared this with the linear density observed in previous research (Kanao at el., 1992). As for the crowd flow, we compared the characteristics of the simulation with observation data at a soccer stadium. We extracted data on the trajectories of pedestrians from a video of queues in front of the entrance. From the observation data, we determined that the queue had a high density where individuals were standing and a low density where they were moving. For a single queue, our crowd simulation reproduced the density and this characteristic crowd flow.

We measured the formation of a queue for three types of areas: straight, corner, and winding (Fig.5). In our simulation, 200 agents were distributed at random, and then they all moved toward the queue area. After all agents were in the queue, the entrance was opened, and we measured the flow of the crowd as they entered.

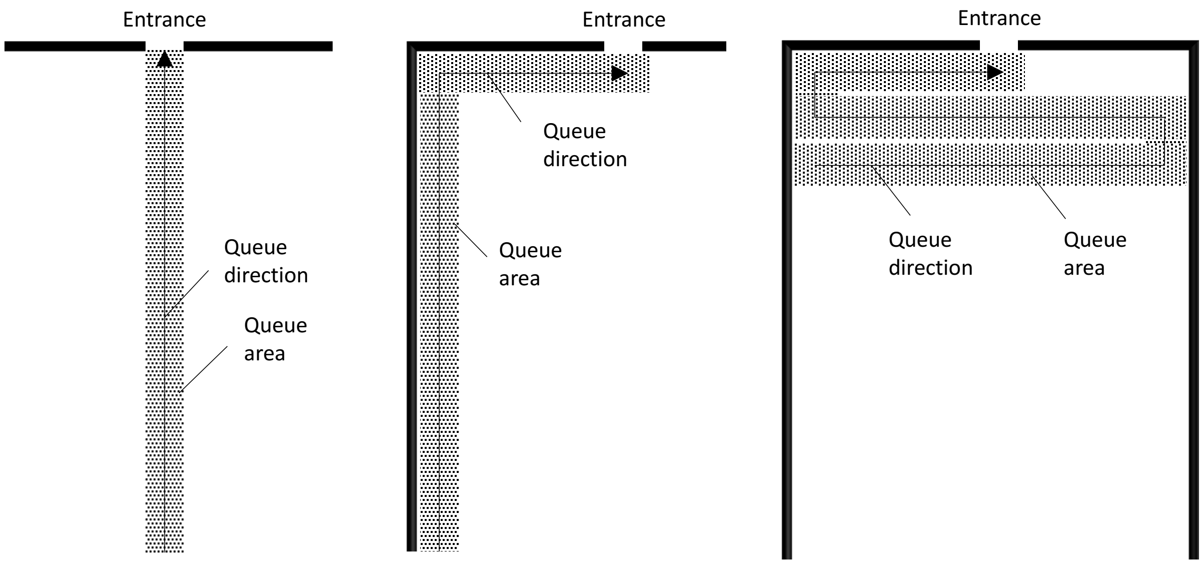


Fig. 5: Three types of queue formations

2.3 Application to a Large-scale Facility

We applied the crowd simulation to a large-scale commercial facility that is currently under construction, in order to evaluate crowd safety during a special event. The entire site covers an area of approximately 38,000 square meters. The number of visitors is estimated to be 10,000 people, and the time is from 7:00 (3 hours before opening) to 11:00 (1 hour after opening). The six routes are based on the existing public transportation in this area, and the proportion of individuals on each route is based on transport planning figures. We considered the queue areas in front of each of the four entrances. The shapes of the queue areas include straight, corner, and winding, as needed to adapt to the surrounding environment (Fig.6).

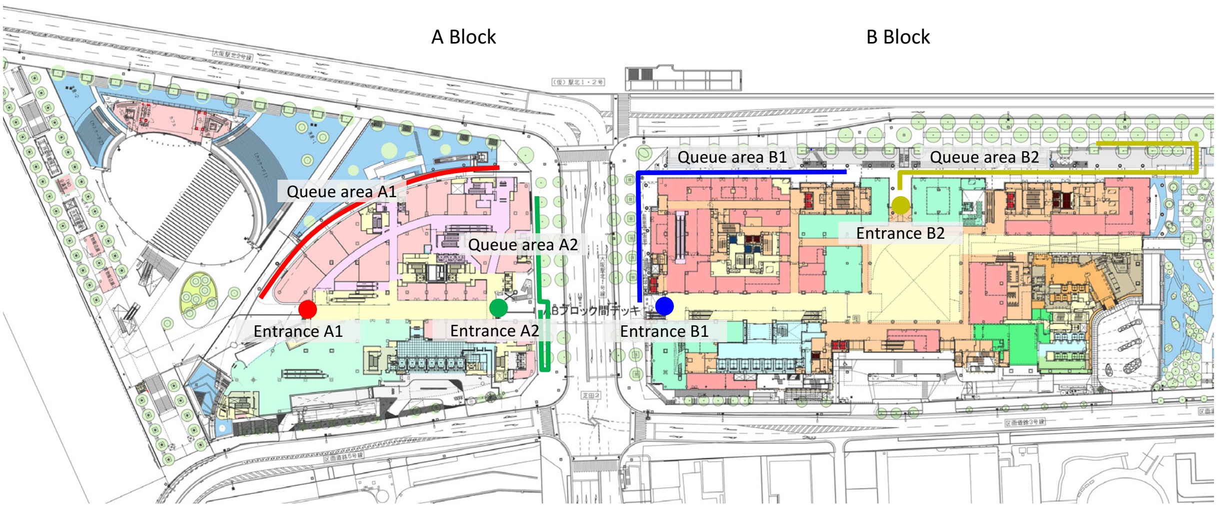


Fig. 6: Large-scale commercial facility

3. RESULT AND DISCUSSION

3.1 Linear Density in the Queue

In our model of crowd movement in a queue, we used an ellipse instead of a circle so that we could consider the difference of shoulder width and body thickness. We consider this shape is exclusive to the agent. When the shoulder width is fixed at 60 cm and the body thickness is changed in increments of 5 cm, ranging from 25 cm to 60 cm, changes in the linear density of the queue are shown in Fig. 7. According to the previous observation data

(Kanao at el., 1992), 77.6% of linear densities for a single queue are distributed between 1.6 and 2.4 people/m. The average is approximately 2.0 people/m and the standard deviation is approximately 0.4 people/m. In our model, if the body thickness is 30 cm, the linear density is approximately 2.0 people/m. However, it is appropriate to change the linear density depending on the conditions, and our model enables the density to be calibrated by adjusting the shape of the ellipse.

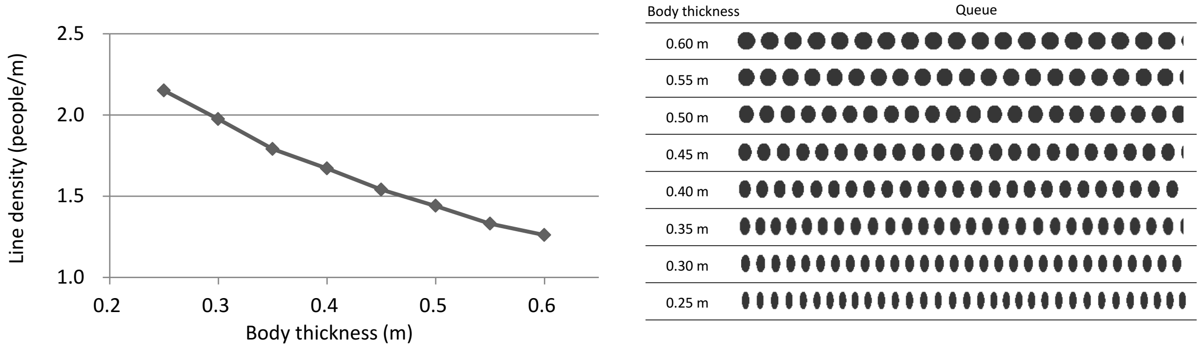


Fig. 7: Changes of linear density by parameter

3.2 Reproduction of Crowd Flow in a Queue

To reproduce a pattern observed in the flow of crowds in a queue, we modeled the situation in which a pedestrian towards the front of a queue temporarily stops. This changes the queue which then consists of high-density standing parts and low-density moving parts. Over time, the high-density parts move backward in the queue. This phenomenon is called a stop-and-go wave.

The upper left-hand side of Fig. 8 shows a stop-and-go wave observed in the queue formed in front of the entrance of a soccer stadium. The upper right-hand side of Fig. 8 shows a stop-and-go wave reproduced by our simulation. The lower part of Fig. 8 compares the distribution of pedestrians as observed with that of the simulation. In the observation data, the queue was formed by one or two rows, whether they were a group or not. The linear density of the moving pedestrians is 1.5 people/m and that of the standing pedestrians is 3.2 people/m. On the other hand, the queue of the simulation is formed by a single row. The linear density of the moving pedestrians is 0.9 people/m and that of the standing pedestrians is 2.0 people/m. Because the number of rows is different between the observation and the simulation, a simple comparison is impossible. However, the ratios between the density of moving pedestrians and that of standing pedestrians are almost the same. Moreover, the propagation speed of the high-density part in the observed queue is reproduced by calibrating the parameters of C_i and D_i in our crowd movement model.

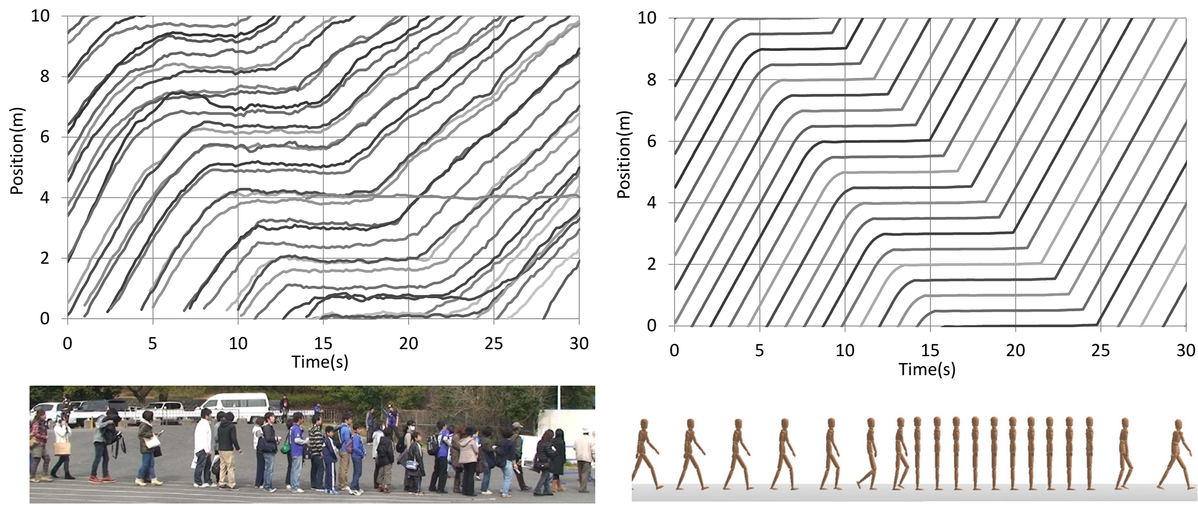


Fig. 8: Reproduction of crowd flow in a queue

3.3 Comparison of Queue Formation Process

Figure 9 shows the results of the queue formation and entry processes for the three types of queue areas. At first, agents are distributed at random positions, and the agents near the entrance move to the queue area. As the queue is formed, the agents who want to join a queue move toward the rear of the queue, where the agent can join the queue.

For a straight queue, it took 2 minutes 30 seconds until all the agents had joined a double-row queue. The maximum linear density was 3.92 people/m, and the length of the queue was 51 m. The corner queue took 3 minutes 58 seconds to finish forming; it was also in two rows. The maximum linear density was 3.74 people/m, and the length of the queue was 53.5 m. The winding queue took 4 minutes 29 seconds to finish forming a double queue. The maximum linear density was 3.60 people/m, and the length of the queue was 55.5 m. These results indicate that the differences in the linear density and the lengths of the queues are not significant, but the difference in the time it took to finish forming the queue was large. The time depends on the environment of the queue area, such as if a straight queue has walls on either side, or if a corner or winding queue can only be accessed from one side.

While the queue was being formed, the entrance was closed. When the queue was finished forming, every agent was in the queue, and the linear density was maximized, the entrance was opened. The graph of Fig. 9 shows the number of agents in the queue after the entrance was opened. The entrance time for the straight queue is shortest. The time was 135.9 seconds, and the average rate of flow at the entrance opening was 0.98 people/m/s. Because the width of the opening and the that of the queue were the same, the flow rate maintained a high value compared with other queues. However, the flow rate was smaller than the empirical flow rate at a simple opening (1.5 people/m/s). The flow rate of 2.22 people/s (1.49 people/m/s) was approximately reproduced by our model when using a 1.5 m opening (Fig.9: the graph of 'None'). The delay occurred when an agent in a queue started to move behind the agent in front of him, but was delayed by the model of following behavior. The second shortest entrance time was measured with the corner queue. The time was 157.1 seconds, and the average flow rate at the entrance opening was 0.85 people/m/s. The three right-angle corners reduced the flow. The longest entrance time was measured with the winding queue. The time was 180.3 seconds, and the average flow rate at the entrance opening was 0.74 people/m/s. The crowd flow with the winding queue was less than that of the corner type due to the three corners that turned it back 180 degrees.

From this comparison, we see that the crowd flow increases if the queue is as wide as the opening. However, the flow rates for every type of queue were less than the empirical flow rates with a simple opening (1.5 people/m/s). Moreover, we note that the number of corners in a queue also reduces the flow rate.

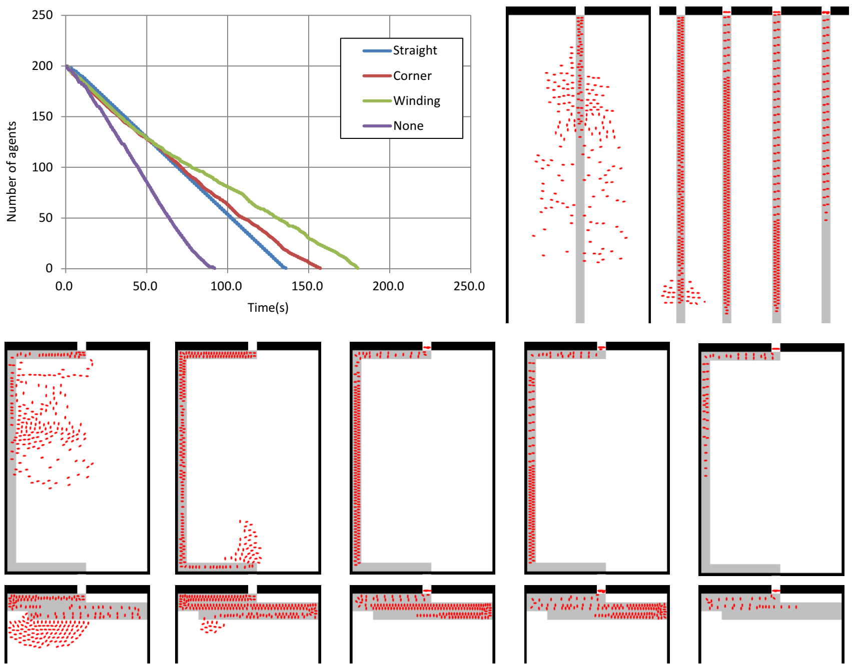


Fig. 9: Entrance time and queue formation process

3.4 Application to a Large-scale Facility

Figure 10 shows the application of our simulation to a large-scale facility that is currently under construction. The person in charge of crowd security uses a simulation movie to explain the specific queue areas and the expected flow of visitors. Safety measures are shared among the organizers when a special event is going to be held. A method that uses visual information assists non-experts, for whom numerical information may not be useful, to imagine the crowd flow.

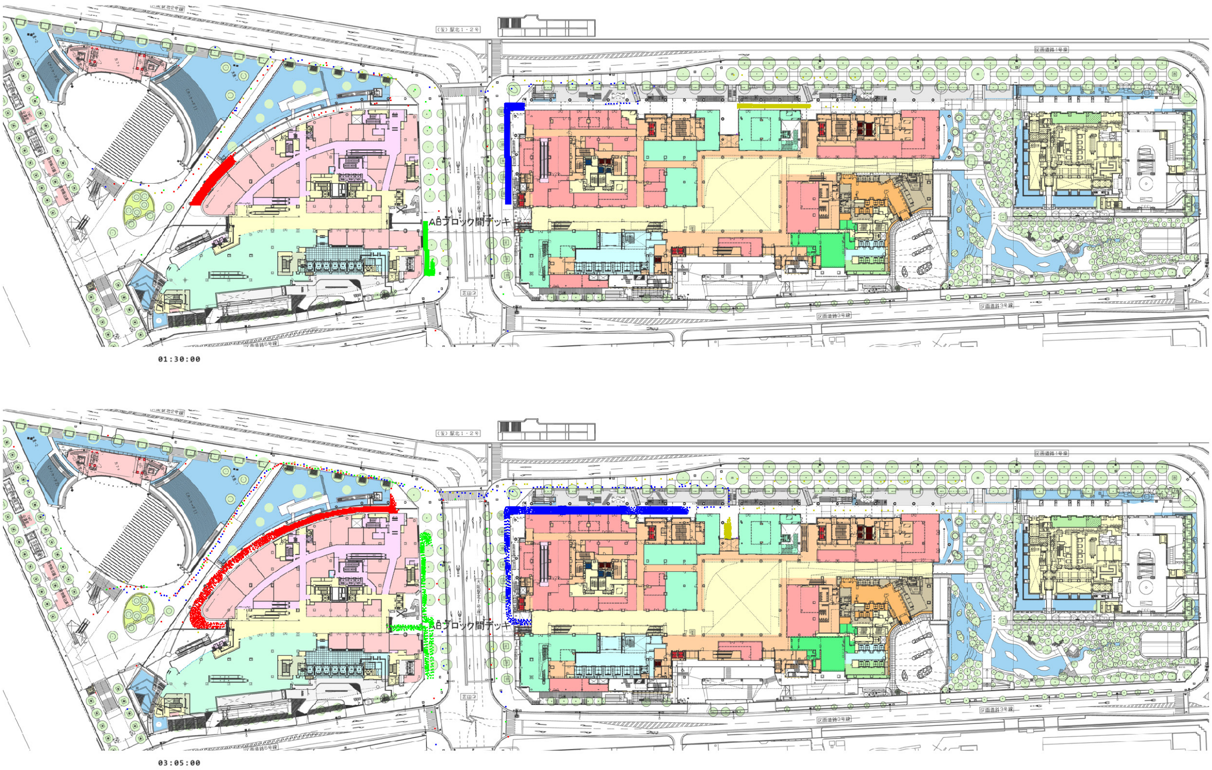


Fig. 10: Application to a large-scale facility

4. CONCLUSION

This study modeled the microscopic interactions between agents to develop an agent-based crowd simulation that enables the reproduction of the macroscopic phenomena of the flow of a crowd in a queue. In addition, we applied the simulation to a large-scale facility that is currently under construction and share visual information about the crowd flow that can be used when a safety plan for the facility is determined. The results are as follows.

To reproduce the crowd flow in high-density queue, we implemented an ellipse-based collision detection process based on the social force model. In consequence, if the body thickness was 30 cm, the linear density was approximately 2.0 people/m. We also reproduced a feature of queues called stop-and-go waves. By comparing the simulation with observed data, we determined that the ratios between the densities of moving and stationary pedestrians were almost same. Moreover, the propagation speed of the high-density part of the observed queue was reproduced by calibrating the parameters. The shape of the queue area was also determined to affect the flow of the crowd. However, the flow rates for every type of queue were less than the empirical flow rates at a simple opening because of behavior when following. The number of corners in a queue also reduced the crowd flow.

As a result of the application of this method to the simulated crowd at a large-scale urban facility, safety measures can be shared among the organizers when a special event is going to be held. A method such as this, which uses visual information, enables crowd flow to be imagined even by non-experts, for whom numerical information may not be useful.

5. ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number 24760490.

6. REFERENCES

Berg, J. et al. (2008). Reciprocal velocity obstacles for real-time multi-agent navigation, Proceedings IEEE International Conference on Robotics and Automation, 1928–1935.

Burstedde, C. et al. (2001). Simulation of pedestrian dynamics using a two-dimensional cellular automaton, Physica A 295, 507–525.

Helbing, D. et al. (2000). Simulating dynamical features of escape panic, Nature 407, 487–490.

Kaitsuji, M. et al. (2010). Prevision of an interrupted flow of the crowd in high-density and analysis of the factors & reasons why risk could not be avoided at large-scale event "Japan Countdown 2001", Memoirs of the Graduate Schools of Engineering and System Informatics Kobe University, 1–13.

Kanao, M. et al. (1992). On the linear density and personal distance in waiting lines, Summaries of technical papers of Annual Meeting Architectural Institute of Japan. E-1, 721–722.

Lemercier, S. et al. (2012). Realistic following behaviors for crowd simulation, Computer Graphics Forum Vol. 31, 489–498.

DEVELOPMENT OF VIRTUAL REALITY APPLICATIONS FOR THE CONSTRUCTION INDUSTRY USING THE OCULUS RIFT™ HEAD MOUNTED DISPLAY

David S. Lyne
Makemedia Ltd, Brighton, UK

ABSTRACT: *3D visuals are a fundamental part of virtual reality that we often take for granted. Yet when we simulate 3D we often neglect to accurately reproduce the basic concept of depth perception. This document discusses possible applications for stereoscopic head mounted displays within the context of the construction industry and seeks to highlight the technical considerations of using such technologies.*

KEYWORDS: *Oculus Rift, Construction, Simulation, Stereoscopic, 3D, Head Mounted Display, Virtual Reality*

1. INTRODUCTION

3D visuals are a fundamental part of virtual reality that we often take for granted. Yet when we visualise 3D we often neglect to consider binocular disparity. Binocular disparity refers to the difference in image location of an object seen by the left and right eyes, resulting from the eyes' horizontal separation. This is an important factor of depth perception that helps us to truly perceive an environment (**Anderson,** 2000). So it follows that it is the use of stereoscopic display technologies that provides the final piece of the puzzle needed to exploit virtual reality to its fullest potential.

The basic technique of stereoscopic displays involves the presentation of two offset images that are displayed to the left and right eyes. The offset between the two images accounts for the IDP (the interpupillary distance) so that the human brain is provided with the additional information needed to combine the images and thus enhance the perception of depth (Anderson, 2000).

Whilst stereoscopic technologies have been used for some time in virtual reality, they have traditionally been confined to the realm of very high-end and expensive simulation applications. However, in recent years there has been a consumer led desire for such products in entertainment markets such as television, film and gaming. This has significantly driven down the cost of the necessary core display technologies and, just as we have witnessed in the last few decades with mass market 3D gaming products, these technologies will inevitably trickle down to be adopted more widely in professional virtual reality applications.

Citation: Lyne, D. S. (2013). Development of virtual reality applications for the construction industry using the Oculus Rift™ head mounted display. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Fig. 1: The Oculus Rift at Makemedia, Brighton

The latest consumer product that is sure to influence professional virtual reality applications is the Oculus Rift™. The Oculus Rift is a high field of view (FOV), low-latency, consumer-priced virtual reality head-mounted display (HMD) (Figure 1).

The Oculus Rift has not yet been launched as a commercial product. However, a small number of developer kits have been made available, which has facilitated some early software prototyping, enabling us to explore its potential within the context of virtual reality for construction applications.

For development of such applications, we are using a number of different visualisation toolkits. The Oculus Rift development kit is supplied with an out-of-the-box integration module for Unity 3D™, which is facilitating rapid prototyping. However, we have also successfully developed custom integrations of the Oculus Rift with visual solutions such as Presagis Vega Prime™.

Here at Makemedia, our team has a varied background in military aircraft simulation, games, architecture and construction simulation. This provides us with the perfect set of skills to develop complex immersive environments using advanced stereoscopic visual technologies such as the Oculus Rift.

2. USES FOR CONSTRUCTION APPLICATIONS

Using Unity 3D we have already converted many of our virtual environments to integrate with the Oculus Rift. Figure 2 shows an image from one of our 3D environments, which demonstrates the stereoscopic projection required for the Oculus Rift. The environment depicts one of five 'time-slices' of a construction project that were modeled to aid training scenarios used at the ACT-UK simulation centre.

Fig. 2: Makemedia have produced 3D models of construction sites for ACT-UK and BLSC Australia.

Practically any 3D virtual reality application can be modified to work with the Oculus Rift. Below we discuss specific areas where the Oculus Rift offers an advantage for visualising an environment over traditional display methods.

2.1 Health and Safety Training

Health and safety training provides an ability to ‘fly’ through a virtual construction site, inspecting building work in close detail in order to provide an opportunity to make decisions in a safe and controlled environment, supported by individual observation, evaluation and feedback.

The enhanced perception of depth provided by the Oculus Rift facilities a heightened awareness of a scene that can benefit the inspection of building work in a virtual environment. Visual cues that were once less apparent on a 2D display are perceived to the same extent that they would be on a real construction site, which should lead to a better correlation between virtual and real world training methods.

2.2 Virtual Maintenance Training

Virtual Maintenance Training (VMT) is a training method that includes computer-based interactive 3D simulations of virtual equipment that replicates the actual real life vehicle or device. Its aim is to safely teach workers to correctly service, repair and maintain equipment.

The accuracy of stereoscopic vision offered by Oculus Rift is particularly beneficial for VMT applications, since it provides a true sense of depth and scale to the virtual representation of the simulated device and its subsidiary components.

As depicted in Figure 3, which shows a VMT application for a junction box repair exercise, this type of application is generally heavily reliant on a 'point-and-click' interface design to select appropriate tools and interact with the 3D objects. From our research it is apparent that such an interface does not translate particularly well to HMDs. However, solutions to such problems are conceivable and are discussed in this document under the heading 'Technical Challenges'.

Fig. 3: A Virtual Maintenance Trainer Application for a Junction Box Repair Exercise

2.3 Cost Effective Alternative to Large Multi-Projector Displays

Large multi-projector curved display solutions are used throughout the construction industry to provide the wide field of view necessary to immerse the user. Such displays can often be extremely expensive to purchase and maintain, with a single projector that is bright enough for large displays costing at least fifty times more than a single Oculus Rift head set (Projector Central, 2013). Furthermore, unlike large display solutions, this hardware can be used in conjunction with a laptop to become fully portable.

The horizontal field of view offered by the Oculus Rift is over 90 degrees, almost completely filling the user's field of view (Land, 2012). This, combined with the head tracking sensor capability, gives an effective 360 degree field of view.

It must be noted that an area where the Oculus Rift does not currently compare to existing multi-projector solutions is resolution. When released the Oculus Rift will support a resolution of 1080p (Oculus VR, 2013). This resolution shared between both eyes equates to an overall resolution of 960x1080 pixels. In comparison, a multi-projector display will often use two to four 1080p projectors within a comparable field of view. However, with the advent of 4K HD display screen technology already coming to market (Bell, 2013), this is an area that is likely to equalize over the next few years (Hopping, 2013).

2.4 Visualization of BIM Data

Building Information Modeling (BIM) is the process of generating and managing data about a building during its life cycle. We are currently in the process of developing applications to visualize BIM data and we see real advantages to using stereoscopic visualization for this purpose.

The Oculus Rift provides a portable solution to a visualization tool for designers, architects, town planners, sales/marketing personnel and construction workers to see a construction at any stage of the build process.

Whilst BIM data 3D models are often geometrically complex, they generally lack important visual features such as surface textures (O'Brien, 1997) that are key in simulating the perception of depth and parallax (the difference in the apparent position of an object viewed from multiple viewpoints) on a 2D display. The use of the Oculus Rift has the potential to minimize some of these deficiencies, due to its realistic representation of depth perception.

3. TECHNICAL CHALLENGES

From our initial prototyping with the Oculus Rift we have uncovered a number of technical challenges that are associated with HMDs in general. These are discussed below.

3.1 Human-Machine Interface (HMI) Considerations

Traditional virtual reality applications generally rely on a conventional user interface design that incorporates a 2D overlay (or Head-Up Display) to provide feedback to the user in text form or to provide additional methods of interacting with an environment. Many of these techniques do not translate well to HMDs for the reasons discussed below.

3.1.1 Decrease in Screen Space 'Real Estate'

User interface elements cannot be positioned near the edges of the screen; once wearing the Oculus Rift these areas are very much in the peripheral vision of the user.

Whilst it is possible to move such elements nearer the centre of the image, this approach has the obvious drawback of obscuring the user's vision of the 3D environment.

We are therefore required to utilize a more creative approach to convey information to the user. An increased usage of recorded speech is a good first step. But in addition, more of the user interface elements need to be integrated into the 3D environment. For example, a virtual smart phone could be utilized so that in the event that a certain piece of information needs to be conveyed to the user, the phone will ring and the user can then take the call in order to be presented with images and text on the virtual smart phone's display.

In summary, whilst user interface design is a challenge, it does bring about some exciting possibilities which could compel us to develop our applications in a way that is actually more intuitive to the user.

3.1.2 No Visibility of the Outside World

A drawback of total visual immersion is the lack of visibility of the external world. An obvious implication of this is that it is impossible to see one's own hands with the HMD on. Conventional VR applications rely on complicated user input devices with many buttons and inputs, such as keyboards, mice or joysticks, and these inevitably become difficult to operate whilst wearing the Oculus Rift.

One simple solution to this problem is to use the head tracking feature of the HMD as the pointing device. When the user wishes to select an object in the virtual environment, he/she can simply look directly at the object then combine this with a single button press or voice activation command to initiate the interaction.

Some more exotic solutions to a pointing device are feasible. For example the Razer Hydra™ is an inexpensive commercially available product that can provide a simplified representation of your own hands in 3D space (Figure 4).

Fig. 4: The Razer Hydra

Depth sensors such as the Microsoft Kinect™ are also possible inexpensive solutions to track hand movement and 3D gestures (Holloway, 2013). High-end products, such as the IGS Glove, are also available to provide full tracking of the hands and fingers (Figure 5).

Fig. 5: The IGS Glove

Currently, the Oculus Rift development kit does not provide an integrated camera. However, whilst at present unconfirmed, it is possible that the final commercial version will include this feature (Verry, 2013). This would certainly open up the possibility of using augmented reality (AR) to help solve the aforementioned challenges. *Augmented reality* is a technique to combine real-world environments with computer-generated sensory input.

Take, for example, an excavator trainer: a conventional simulator would normally use a real cabin combined with a panoramic display to simulate a virtual environment out of the window (Figure 6). With an HMD solution and augmented reality, the real image of the cabin as perceived by the integrated camera could be composited in real-time with the 3D virtual environment.

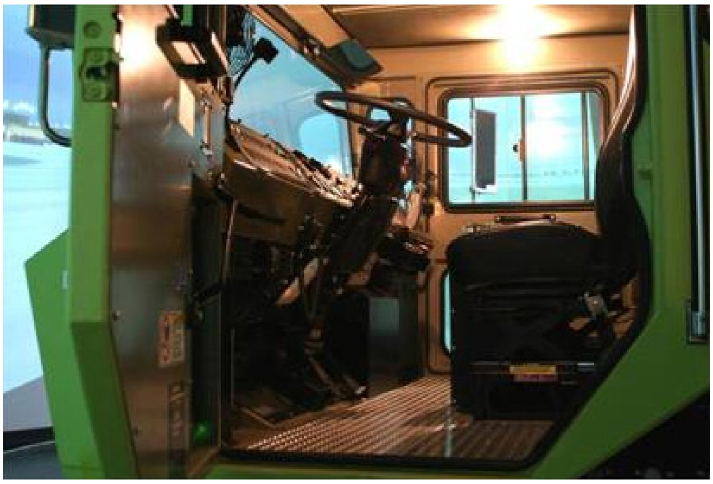


Fig. 6: Cabin with virtual environment projected out-the-window

It should be noted that HMD technologies specifically designed for AR are already available on the market, such as the Vuzix STAR 1200. However, as far as we are aware the field-of-view of this and other similar devices are far less than the Oculus Rift. For example the field-of-view of the Vuzix STAR 1200 is 23-degrees (Vuzix, 2013) compared to the Oculus's 90-degree field-of-view. Such narrow field-of-views will inevitably compromise immersion.

Another example of the use of AR in this context is to facilitate the combination of live trained actors and virtual reality as used by the ACT-UK simulation centre in Coventry (see Stockdale 2010 for more information on the ACT-UK centre).

By using a combination of the Oculus Rift and green screen technology it is conceivable that the user will experience a much more complete projection of the virtual world around the live actors than is practical with conventional curved screen technologies.

The photograph in Figure 7 was taken at the ACT-UK simulation centre and displays the projection screen used to depict the virtual environment. Whilst this current solution provides a wide field of view by the standards of traditional display technologies, it is quite apparent that much of the environment is either provided by a static backdrop or not represented at all. An HMD solution would provide the possibility of rendering much more of the environment as a dynamic virtual representation including the ground and the construction site environment at higher elevations.

Fig. 7: ACT-UK Simulation Centre

4. SUMMARY

Our experimentation with the Oculus Rift is certainly in the early stages, but already we have explored a number of interesting use cases via some initial prototyping.

We propose that the enhanced simulation of depth perception could benefit health and safety applications, virtual maintenance training and BIM data visualisation. In addition it is likely that the HMD can reduce costs by replacing expensive traditional multi projector display technologies with its inherently large field of view and head tracking technology.

There are challenges to user interface design. However, these could provide us with opportunities to enhance the user experience by challenging the software developer to create a more natural user interface than the traditional "point and click" design.

In the future we hope to see further improvements to the hardware specification of the Oculus Rift. Specifically we see the need for improved resolutions beyond HD in order to facilitate the replacement of all existing traditional high-end display technologies. With the advent of 4K Ultra HD displays already coming to the market coupled with the inevitable competition from rival HMD manufactures, this is something that is likely to take only a few years. In addition, we would like to see the inclusion of an integrated camera with the Oculus Rift to facilitate augmented reality application development.

Moving forward we are keen to explore how this technology can benefit the end user. To a large extent we are driven in this regard by the vision of our customers and so our hope is that this paper can spark further debate in order that other uses can be imagined.

5. ASSOCIATED TECHNOLOGIES

Oculus Rift by Oculus VR. http://www.oculusvr.com

Razer Hydra by Sixense Entertainment. http://www.razerzone.com/gb-en/gaming-controllers/razer-hydra

IGS Glove by Synertial. http://www.animazoo.com/content/igs-glove

Unity 3D by Unity Technologies. http://unity3d.com/

Vega Prime by Presagis. http://www.presagis.com/products_services/products/modeling-simulation/visualization/vega_prime/

6. REFERENCES

ACT-UK (2013) *ACT-UK Simulation Centre* [online]. Available at: http://www.act-uk.co.uk [Accessed 17 July 2013]

Anderson, B. L. (2000) ‘Depth Perception’ in Kazdin A.E (Ed.) *APA's Encyclopaedia of Psychology*, Washington, USA: APA

Bell, L. (2013) *Asus 4K UHD monitor goes on presale in US for $3,499* [online]. Available at: http://www.theinquirer.net/inquirer/news/2279303/asus-4k-uhd-monitor-goes-on-presale-in-us-for-usd3-499 [Accessed 9 August 2013]

BLSC (2013) *Building Leadership Simulation Centre* [online], Available at: http://www.blsc.com.au [Accessed 17 July 2013]

Gorman, M. (2013) *Oculus Rift HD prototype VR headset appears at E3* [online]. Available at: http://www.engadget.com/2013/06/11/oculus-rift-hd-prototype-vr-headset-hands/ [Accessed 15 July 2013]

Holloway, J. (2013) *Oculus Rift + Microsoft Kinect = full-on Virtual Reality?* [Online]. Available at: http://www.gizmag.com/inition-oculus-rift-vr/27701 [Accessed 17 July 2013]

Land, B. (2012) *HMD Specs Comparison: Oculus Rift vs. Silicon Micro Display ST1080 vs. Sony HMZ-T1* [online]. Available at: *http://www.roadtovr.com/2012/08/11/hmd-specs-comparison-oculus-rift-vs-silicon-micro-display-st1080-vs-sony-hmz-t1-937* [Accessed 17 July 2013]

O'Brien, J. M. D. (1997) *Texture and Motion Cues in Slant Perception*, PhD thesis, University College London, London

Oculus VR (2013) *Oculus at E3 2013* [online]. Available at: http://www.oculusvr.com/blog/oculus-at-e3-2013. [Accessed 10 August 2013]

Projector Central (2013) *Christie HD10K-M Projector* [online]. Available at: http://www.projectorcentral.com/Christie-HD10K-M.htm. [Accessed 10 August 2013].

Stockdale, L. (2010) *ACT-UK, Simulating Success* [online]. Available at: http://www.insidehousing.co.uk/simulating-success/6510432.article [Accessed 16 July 2013]

Hopping, C. (2013) *4K screens coming to Android smartphones and tablets?* [online]. Available at: http://www.knowyourmobile.com/google/20832/4k-screens-coming-android-smartphones-and-tablets [Accessed 10 August 2013].

Verry, T. (2013) *GTC Oculus VR Reveals Future of Oculus Rift at ECS* [online]. Available at: http://www.pcper.com/news/General-Tech/GTC-2013-Oculus-VR-Reveals-Future-Oculus-Rift-ECS [Accessed 16 July 2013].

Vuzix (2013) *Vuzix STAR 1200 Augmented Reality System* [online]. Available at: http://www.vuzix.com/augmented-reality/products_star1200.html#TechSpecs. [Accessed 10 August 2013].

3D BARRIER-FREE VERIFICATION FOR WHEELCHAIR ACCESS

Yoshihiro Yasumuro, Shizuka Kusakabe & Hiroshige Dan
Kansai University, Japan

Masahiko Fuyuki
Kio University, Japan

ABSTRACT: *This paper proposes a new methodology for identifying barriers encountered by wheelchair users in daily life spaces. Currently, barrier-free designs are required not only for newly constructed buildings, but also when renovating existing facilities and public spaces. However, the arrangement of furniture, equipment, and many other objects in a space often impose barriers, and even the simple bumps and steps on pathways can obstruct wheelchair passage. Furthermore, it is often difficult for administrators to envisage the full reality of barriers in their facilities because potential obstacles can be created inadvertently by a variety of objects that have complicated three-dimensional (3D) geometries. In such cases, their existence will normally remain unknown until someone actually tries to transit the area using a wheelchair. Our approach aims to capture the overall dimensions of target spaces by collecting and combining depth images taken using a hand-held RGB-D camera (also commonly referred to as a ranging camera), and then to navigate a virtual wheelchair through the target space in a computer simulation to check for obstacles. The practical egomotion capabilities of RGB-D camera sensors within actual environments make it possible to achieve real-time simultaneous localization and mapping (SLAM) functionality, which is necessary for creating accurate 3D location maps. The Microsoft Kinect™ sensor, which was originally designed as a user interface for home-use video games, is a good example for a low-cost, compact RGB-D camera. Since the Kinect device is sufficiently compact for use when capturing arbitrary objects in situ, we adopted it for use in our study and applied a SLAM technique to perform barrier checks. Our simulation employs 3D projections of all objects and wheelchair transit volumes onto a floor plane in order to detect potential obstacles. We implemented our proposed method on a laptop personal computer (PC) and collected data from actual classroom and common space locations in a university. The experimental results of our method showed effective functionality in terms of practicality and usability.*

KEYWORDS: *Wheelchair user, Barrier-free, RGB-D camera, Free-hand scan, Obstacle check, 3D model*

1. INTRODUCTION

1.1 Background

The rapidly increasing number of elderly people in society together with the declining birth rate has become a serious issue in Japan. Furthermore, society is expected to be as accommodating to those with physical handicaps as it is to people without such handicaps and is working on overcoming numerous barriers. For example, newly built buildings and facilities are progressively being designed to be barrier-free, and there are ongoing efforts to renovate residential and daily life environments in order to provide easy access to schools, shops, and other public places for wheelchair users. However the continued existence of the barriers that remain in pre-existing facilities highlight the inconveniences faced by wheelchair users as they attempt to move around in society.

Citation: Yasumuro, Y., Kusakabe, S., Hiroshige Dan, H. & Fuyuki, M. (2013). 3D barrier-free verification for wheelchair access. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Fig. 1: Example of on-site check for accessibility by a wheelchair user (Kumagaya City Homepage)

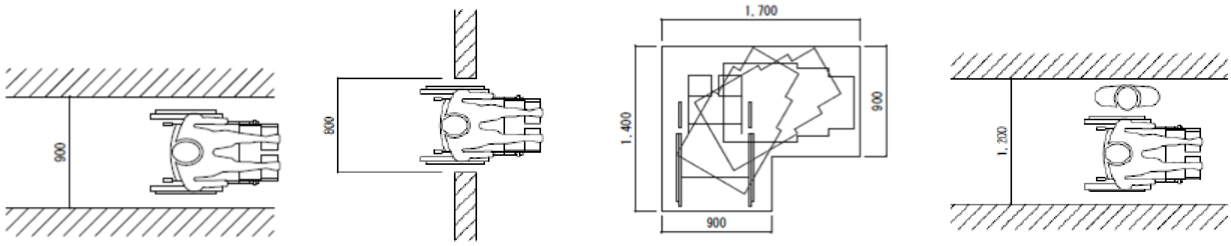
As a side issue, by providing information on the locations of restrooms equipped to service the physically challenged as well as the location of uneven surfaces on pathways, barrier-free maps are gradually becoming familiar as informative tools for elderly people and wheelchair users. In recent years, such maps have been provided on the Web as well as in published form, such as incorporation into booklets. However, the concept of barrier-free mapping is still in the development stage and oftentimes such maps are designed from an administrator's preconceptions rather than from a user's viewpoint. Additionally, while the barrier-free information on such maps is often expressed with specific pictograms designed by industrial standard bureaus or ministries, there are also numerous unique pictograms created and used by local governments, and there has been little effort to date to achieve uniformity. Furthermore, information regarding barrier information details and the investigative methods used to confirm the validity of barrier-free maps differ from place to place. As a result, the barrier-free maps themselves are not always trusted by their intended users.

This paper focuses on the investigative methods used to detect barriers to wheelchair users. We begin by acknowledging that administrators face difficulty in fully comprehending potential barriers in their facilities, especially since many spaces are filled with a variety of objects with complicated three-dimensional (3D) geometries, unless they bring in an actual wheelchair and user into the space to physically verify accessibility (see Fig. 1). As a result, one of the major difficulties involved with existing barriers is the labor cost related to identifying such barriers and determining the degrees of difficulty they impose. Manual inspections are supposed to be conducted by the care-managers or environmental welfare coordinators responsible for evaluating such barriers, and efforts are expected towards the redesign and renovation of existing buildings and facilities into barrier-free environments.

This paper proposes an effective method for investigating the existing physical barriers for wheelchair users that utilize an RGB-D camera, which is capable of compiling depth image information on physical locations. The contact-free and speedy measurement capabilities of RGB-D cameras make it easy to collect onsite information on geometric conditions, and then to compile this data into digitized 3D models. Those 3D environmental models can then be examined in various ways to detect obstacles, and thus eliminate the need to actually bring a wheelchair and user to the target site.

1.2 Mobility and transferring conditions for wheelchairs

To allow wheelchair users free and unencumbered access, a certain amount of space is required for the user's body, hands, and arms when maneuvering the wheelchair. This requirement is in addition to the width of the wheelchair base itself. Referring to the Japanese Industrial Standards (JIS), for example, regulations call for pathway widths of more than 90 cm and doorway widths of more than 80 cm in order to ensure wheelchair accessibility. However, turning a wheelchair also requires a specific minimum space, and it is also important to consider normal two-way pedestrian traffic in public spaces to ensure that sufficient space is available for passing when necessary. Furthermore, it is necessary to ensure that pathway surfaces are sufficiently smooth, and that any slopes are gradual, with specific design elements incorporated if there are differences in floor heights (Osaka Association of Architects & Building Engineers, also see Fig. 2).



(a) (b) (c) (d)

Fig. 2: Fundamental spatial conditions for wheelchair mobility: (a) basic pathway width, (b) doorway, (c) turning space requirements, and (d) passing another person

2. PROPOSED METHOD

2.1 Overview

For comparatively small spaces such as private residences, conducting manual inspections for wheelchair barriers may not require excessive time or labor because the points to be checked are typical and predictable. In contrast, sorting out potential danger spots and barriers in public sites and commercial facilities can be a large-scale job. Furthermore, there is much wider variety in the type and severity of potential barriers. Accordingly, our basic approach involves collecting 3D data on all possible barrier locations with an easy-to-use tool, then conducting in-depth inspections virtually using a personal computer (PC). To realize virtual inspections that match the actual physical conditions of the site in question, we employ an RGB-D camera and an effective registration technique as a 3D captor system. RGB-D cameras can take depth images and send them

to a host PC in real-time, which is suitable for implementing simultaneous localization and mapping (SLAM) techniques (Newcombe et al. 2011). The depth images are aligned with each other using a shape matching process (Chen and Medioni 1992), as well as for estimating the camera position and orientation so that the target location can be captured by a series of different angle frames, each of which has a limited field of view (FOV). The aligned depth image has a 3D mesh surface with the same geometry and the scale of the actual scene. Within the 3D mesh, we can then check the point-to-point distances and the volume sizes of the open spaces while comparing them to the size of a wheelchair and its motion trajectories. The conditions described in the previous section can be taken into account, since the conditions can be expressed on a two-dimensional (2D) map subset of our 3D map geometry.

This framework is similar to the performance-based approach for the wheelchair accessible route analysis described by Han et al. (2010). However, whereas Han's method is based on a 2D plan, we started from detailed 3D shape models of actual environments. Using our method, as-built situations and as-is conditions with extra objects including a fixture and fittings, and even temporally placed objects, can be detected as potential barriers. The noteworthy contribution of our method is its ability to preserve the 3D configuration of the potential barrier components in the environment, which can then be simplified via a basic 2D image processing in order to detect potential obstructions between the wheelchair trajectory volume and the surroundings. The entire procedure consists of the following three steps (also shown in Fig. 3):

(1) Modeling wheelchair motion trajectory

(2) 3D map generation of the physical environment

(3) Collision detection between the 3D map and the wheelchair trajectory for finding barriers

2.2 3D Map Generation

To capture the 3D shape of the physical scenes, we employed an RGB-D camera that is capable of imaging depth information. Many RGB-D cameras use an active stereovision method that performs triangulation using a pair of calibrated structured light sources and a camera. While existing infrastructure management practices are designed around laser rangefinders with high precision but low capture speeds (Watson *et al.* 2011, Miller *et al.* 2008, Shih *et al.* 2006), the compact RGB-D camera devices developed to capture human motions as video game user interfaces in recent years can capture depth images at high frame rates (Freedman *et al.* 2010). Accordingly, after evaluating the capture speed and compact size of these devices, we determined it would be possible to use one as a portable on-site investigation tool. Table 1 shows the specifications of the Kinect™ sensor RGB-D camera used in our implementation and experiments. We also utilize a point cloud library (PCL), an open source SLAM technique implementation, for constructing 3D maps.

Table 1. RGB-D Camera Specification

Device	Kinect™ for Xbox 360
Field of view	57° (H) × 43° (V)
Depth image size	640 pix (W) × 480 pix (H)
Depth range	0.8 ~ 4.0 m
Frame rate	30 fps

2.3 Wheelchair Trajectory Model

To enable virtual inspections on a PC, it was first necessary to model wheelchair performance so that it could be incorporated into the collected 3D environment. The wheelchair model requirements include all possible spatial volumes the wheelchair and user would occupy in 3D space while simultaneously considering the actual size of a wheelchair carrying a user based on the JIS T9201 industrial standard (see Fig. 4), as well as the minimum volume of space required for the wheelchair's trajectory through the target location. The four steps of the modeling process are provided below:

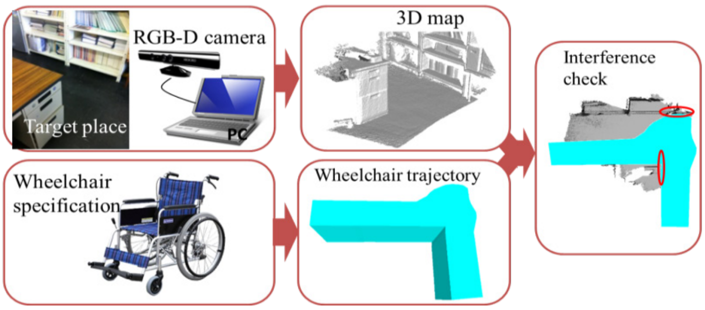


Fig. 3: Conceptual overview of the proposed method

1. A bounding box circumscribing the wheelchair and the user is settled as shown in Fig. 5(a). The height of the box is set to include the user instead of just the wheelchair.

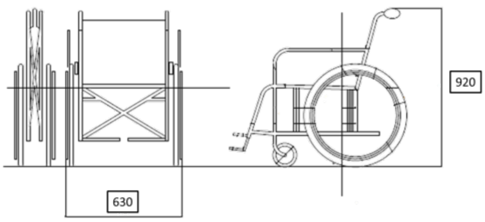
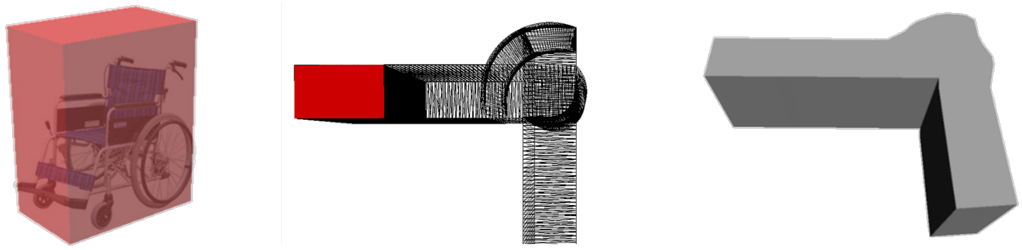


Fig. 4: Standard size of the wheelchair for adults based on JIS

2. The bounding box is moved using translation and rotation. The rotation axis is set to the center of the inner tire, as would occur in the case of an actual wheelchair user making a turn without reverse rolling.

3. The corner positions of the bounding box are recorded during the motion, after which a wire-frame of the trajectory is plotted (Fig. 5 (b)).

4. Finally, the redundant coordinates are removed from the wire-frame and the surface mesh is generated (Fig. 5 (c)).



(a) (b) (c)

Fig. 5: 3D Volumetric trajectory model of a wheelchair for a right-angled turn: (a) static volume of wheelchair with a user, (b) schematic wire-frame for the movement, and (c) final polygonal model

2.4 Barrier Investigation in 3D Map

2.4.1 Checking the Uneven Surface from the Depth Data

Since the highest floor level difference a wheelchair user can traverse while unassisted is approximately 0.02 m, we tested the ability of our methodology to capture this floor height difference using a Kinect™ sensor. Taking

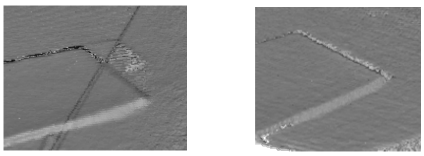
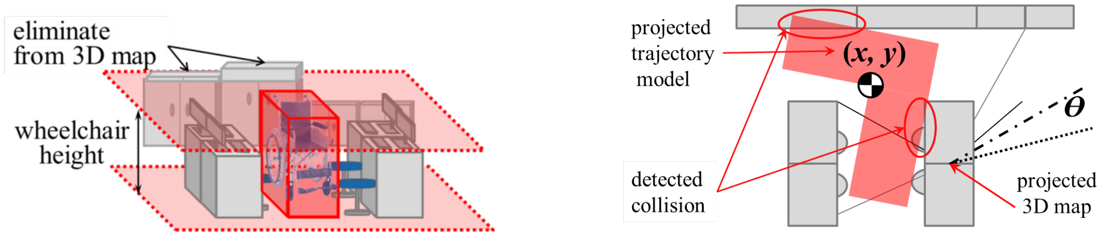


Fig. 6: Example of detected height difference (0.02 m) on the floor: looking down the height gap from 0.7m height at 30° (left) and 60° (right) of view directions

photos within a distance of 0.7 m and within the view direction range of 30° to 60°, the 0.02 m height difference was captured clearly and point-to-point measurement of the gap size was also recorded (Fig. 6)

2.4.2 Barrier Inspection by Collision Detection

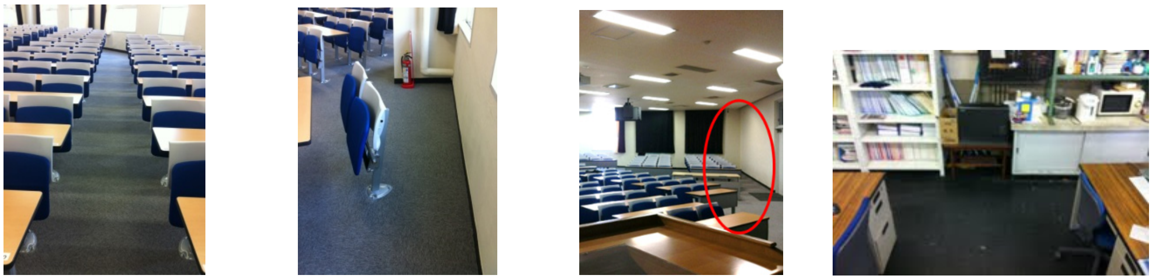
Merging the measurement-based target environment 3D map with the wheelchair trajectory model enables potential physical barriers to be investigated. This process can be accomplished in a straightforward manner by detecting collisions between the 3D map and the trajectory model. However, since both of the modes consist of numerous polygon surfaces, it is still necessary to navigate the trajectory model completely through the 3D map in order to determine whether it can be accomplished without any collisions or contacts between the two. Previously, collision detection techniques developed in the computer graphics field have focused primarily on generating realistic 3D scenes, especially for video games, that require a fast response to contacts between objects. In video games, objects are designed with the smallest number of polygons possible in order to enable the collision detection process to work well. In contrast, depending on the complexity of the location, the number of polygons our 3D map must handle can range from hundreds of thousands to several million.



(a) (b)

Fig. 7: Barrier detection scheme: Within the limit of the wheelchair height (a), 3D map and trajectory modes are projected on to 2D plane, on which collisions are detected as overlapped regions (b)

Accordingly, it was necessary to simplify this collision detection workload by projecting the 3D map onto a 2D space. This was made possible by taking into consideration the point that the wheelchair trajectory will always remain in contact with the floor, and that any possible physical barriers will exist within the height range of the wheelchair and the user. An example of eliminating polygons higher than the wheelchair user in the 3D map and for projecting the remaining polygons onto the floor surface is shown in Fig. 7 (a). The volumetric trajectory model is also projected onto the same surface. Collisions are then detected by the existence of overlapped pixels that belong to both the 3D map and the trajectory model projected onto the 2D plane surface. Again, the clear difference between this method and the method described by Han et al. (2010) is that we started from capturing the environment geometry in situ so that all potential physical obstacles (even those in the air) could be considered during the investigation. Next, the trajectory model is placed at a certain initial position (x_0, y_0) and is translated and rotated within a certain range that covers all possible wheelchair routes within the target location (Fig. 7 (b)).



(a) (b) (c) (d)

Fig. 8: Target positions for experiments at locations (a), (b) and (c) of a large lecture room and (d) of a laboratory

3. EXPERIMENTS

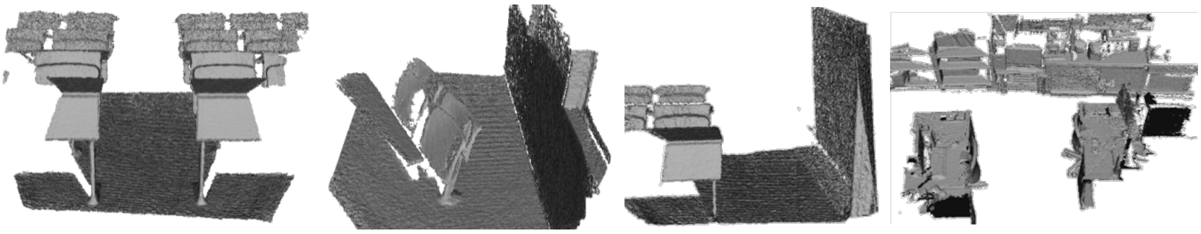
Experiments were then conducted on the campus of our university where there are a number of wheelchair users attending as students. Two locations were picked for our investigation: a typical large lecture room and a comparatively small laboratory space, as shown in Fig. 8. Figure 8 (a) shows a normal pathway between the desks arranged in straight lines. Figures 8 (b) and (c) show a space between a wall and the fold-up chairs, the arrangement of which are not parallel with each other.

Figure 8 (a) also shows a narrow path between the bookshelves, desks, and chairs in a laboratory. Although the arrangement of these items is quite simple, the bottoms of the legs and the desktops themselves cover different amounts of space relative to the floor surface, so determining the narrowest part of the pathway is sometimes difficult. Furthermore, quantitatively estimating the space required to navigate a wheelchair through a particular spot is quite difficult without an actual wheelchair and the user. Figure 9 shows the 3D map created from the captured depth map from each scene shown in Fig. 8. As can be seen in Fig. 9, an overview of Figs. 8 (a) to (c) could be captured in a single shot of the Kinect™ device. The grid size of the voxels needed to register the depth maps was just a 5 mm cube. Figure 9 (d) was constructed by registering six sets of depth data that were obtained from different viewpoints. Among these 3D maps, the smallest model (0.3 million polygons) was found in (c), while the largest model (2.6 million polygons) was found in (d). Figure 10 shows the barrier investigation results. As can be seen in the figure, the desk and chair pathways in Figs. 10 (a) and (b) form complete barriers that prevent wheelchair passage via any route. In contrast, in the case of Figs. 10 (c) and (d), it turns out that no barriers to wheelchair navigation exist. On each image plane, the image size is 640 × 480 pixels, each of which is equivalent to a physical size resolution of 9 × 9 mm.

4. CONCLUSION

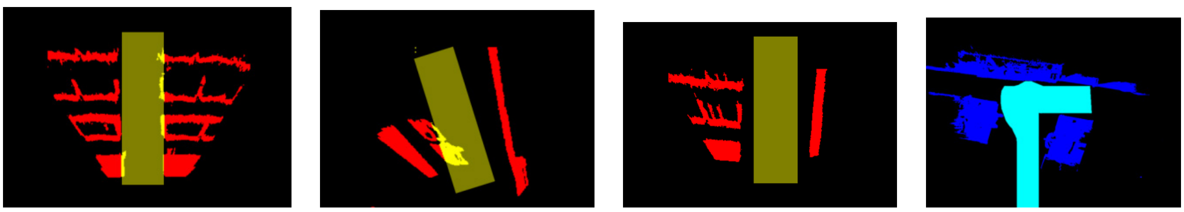
In this paper, we proposed a new method for detecting physical barriers to wheelchair navigation in existing environments. By utilizing a compact RGB-D camera, collecting 3D shape data of the target locations was fast and easy. Furthermore, the acquired data contains rich information about potential physical barriers.

We also developed a barrier detection technique based on collision detection on a 2D image space that preserves candidate barrier information in the initial 3D map. From experiments based on actual locations, it was learned that collecting data and determining the existence of obstacles in real world situations via investigations of virtual wheelchair pathways was achievable. The current implementation is separated in two parts: 3D map generation and 2D barrier detection. Our future work involves combining them together as a packaged application. Validation of wheelchair clearance in situations where no obstacles are detected is also within our plan.



(a) (b) (c) (d)

Fig. 9: Captured 3D map: (a), (b) and (c) are target positions for experiments conducted in a large lecture room, while (d) shows an experiment conducted in a laboratory.



(a) (b) (c) (d)

Fig. 10: Barrier investigation results: The desks and chairs in the (a) and (b) pathways impose complete barriers that block wheelchair passage. In contrast, there is no hindrance to wheelchair navigation in (c) and (d).

5. ACKNOWLEDGEMENT

This work was supported by the Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (24510239).

6. REFERENCES

Kumagaya City Homepage: Kumagaya UD Block (http://www.city.kumagaya.lg.jp/)

Motoda Y., Usami S. and, Ootake R., (2007) *Japan Society of Traffic Engineers (JSCE)Annual Meeting*, Vol. 62. 4-030. (In Japanese)

Osaka Association of Architects & Building Engineers, (http://www.aba-osakahu.or.jp/fukusi) (in Japanese)

Barak Freedman et al. 2010.,　DEPTH MAPPING USING PROJECTED PATTERNS，US patent, US2010/0118123 A1

Shih, N. and Huang, S., (2006), 3D Scan Information Management System for Construction Management." *J. Constr. Eng. Manage.*, 132(2), 134-142.

Watson, C., Chen, S., Bian, H., and Hauser, E., (2011) LiDAR Scan for Blasting Impact Evaluation on a Culvert Structure, *J. Perform. Constr. Facil.*, 10.1061/(ASCE) CF.1943-5509.0000318.

Miller, P. E., Mills, J. P. Barr, S. L. Lim, M. Barber, D. Parkin, G. Clarke, B. Glendinning, and S. Hall, J., (2008) Terrestrial laser scanning for assessing the risk of slope instability along transport corridors, *XXIst ISPRS Congress: Commission V, WG 3*, 495-500.

Han C. S., Law K. H., Latombe J. C, and Kunz C. J., (2002) A performance-based approach to wheelchair accessible route analysis Original Research Article, *Advanced Engineering Informatics*, Vol. 16, Issue 1, 53-71.

Newcombe A. R., Izadi S., Hilliges O., Molyneaux D., Kim D., Davison J. A., Kohli P., Shotton J., Hodges S., and Fitzgibbon A., (2011) KinectFusion: Real-Time Dense Surface Mapping and Tracking, *IEEE International Symposium on Mixed and Augmented Reality*, 127-136.

Chen Y. and Medioni G. (1992) , Object Modelling by Registration of Multiple Range Images, *International Journal of Image and Vision Computing*, 10(3):145-155.

Point Cloud Library (PCL) (accessed in 2013): http://pointclouds.org/

AUTOMATIC GENERATION AND VISUALIZATION OF LOCATION-BASED SCHEDULING

Raj Shah
Liverpool John Moores University, Liverpool, UK

Nashwan Dawood
Teesside University, Middlesbrough, UK

Serafim Castro
Mota-Engil, Portugal

ABSTRACT: *Accurate and visual information of working locations is vital for efficient resource planning and location-based scheduling of earthworks, which is missing in existing linear schedules. Thus, construction managers have to depend on subjective decisions for resources allocation and progress monitoring from location aspects. This has caused uncertainties in planning and scheduling, and consequently delays and cost overruns of projects. A framework of prototype model was developed using the theory of location-based planning to overcome the above issues. This paper focuses on a case study experiments to demonstrate the functions of the model, which includes automatic generation of location-based earthwork schedules and visualization of cut-fill locations on a weekly basis. An arithmetic algorithm was developed by incorporating road design data, sectional quantities, variable productivity rates, unit cost and haulage distance. The model provides weekly information of locations, directions and cut-fill quantities of earthwork under different selections: construction sequences of cut/fill sections, site access points and equipment sets. The paper concludes that the model assists in identifying the correct locations and visualizing the space congestion during earthwork operations. Hence, project resources including heavy equipment and construction materials should be allocated more effectively and correctly from the location viewpoints and ultimately to improve site productivity and reduce production cost in linear projects.*

KEYWORDS: *Earthworks, Cut-fill quantity, Location-based scheduling, Productivity, Visualization*

1. INTRODUCTION

The construction industry has distinct characteristics in comparison with other industries in terms of one-off projects, site production, and temporary organization (Koskela, 2000). The planning and scheduling process of a construction project is a challenging task and the decisions taken in this stage have the foremost impact on the successful execution of a project from its early imaginary to the project completion stage (Ahmed and Walid, 2002). Planning and scheduling involve careful allocation of resources, along a linear construction projects at the required locations and when necessary throughout construction operations. Failure to decide on the optimum work activities with the required resources from location aspects have an adverse influence on project cost, time, space conflicts, and safety of site works in construction projects (Mawdesley, 2004).

Arditi et al. (2002) suggested that earthworks projects require a separate planning task for each project due to the distinctive characteristics of earthworks. The effective application of planning and scheduling techniques: such as CPM and PERT is limited, because the activities associated with linear construction projects such as roads, railways and pipelines are fundamentally different from building projects. Most of the activities in road projects are linear activities. A linear scheduling method has the potential to provide significant enhancement in terms of visual representation from the location aspects, and to progress monitoring because the method allows the project schedulers and construction managers to plan road construction projects visually and determine the controlling activity path and locations (Harmelink and Yamin, 2000). A new methodology with a computer-based model is introduced in this paper to overcome the above issues.

This paper presents a new methodology with a prototype model that generates automatically location-based

Citation: Shah, R., Dawood, N. & Castro, S. (2013). Automatic generation and visualization of location-based scheduling. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

schedules and provides a platform for visualising the scheduling information of earthworks from the location viewpoints, particularly in linear construction projects. The research devises a decision-support tool that aids construction managers in resource scheduling and progress monitoring more effectively, and assists in communicating the scheduling information from the location aspects throughout earthwork operations. In this paper, the location-base scheduling is dubbed as "time-location plan". The remainder of the paper outlines literature review, design a conceptual framework, and details of the prototype model development that includes inputs, processes and outputs. The key output of the model is automatic generation of location-based schedules (time-location plans) with optimised quantities of earthworks, particularly in linear projects. Finally, a case study experiments from a road construction project is illustrated.

2. LITERATURE REVIEW

Earthworks have unique characteristics and take place at the early stages of construction particularly, in linear construction project like road, railways and pipelines. They constitute a major component in road construction, absorb high costs, and there is a need to deal with haul distances for balancing cutting and filling quantities in a cost effective approach (Kim and Russel, 2003). For instance, a study of 145 road projects found that earthworks component was represented around 19.58 per cent of the monetary value of project (Castro, 2005). The earthworks activities also have direct effects in the sequencing of the rest of road activities since earthwork contributes higher percentage in project value. Decisions taken during the planning stage of earthwork operations have high impact on overall performance of the project (Mawdesley, 2004).

Mattila and Abraham (1998) stated that the subjective division of repetitive activities from location to location, the inability to schedule the continuity of resources and display the activity rates of progress, and failure to provide any information of performed work on a project site are key limitations of CPM. Mawdesley et al. (2004) pointed out that CPM networks are more suitable for large complex projects, however, line of balance and linear scheduling methods are more practical for the repetitive and linear construction projects. A linear schedule is used to reduce the interruption of continuous or repetitive activities, to maintain resource continuity, and to determine locations of the activities on any given day from the schedule.

Arditi et al. (2001) suggested that the line of balance technique is an example of linear scheduling method. This technique is based on the hypothesis that productivity for an activity is uniform. In other words, the production rate (productivity) of an activity is linear when time is plotted on the vertical axis, and location of an activity on the horizontal axis (or vice versa). The production rate of an activity is the slope of the production line, and is expressed in terms of units/linear meter per time. Scheduling methods such as line of balance, repetitive scheduling method, time-location matrix model, time-space scheduling method, linear scheduling methods, time-distance diagram and linear-balance diagram are known as 'location-based scheduling'. These methods are based on the theory of location-based planning in the management of construction projects (Kenley and Seppanen, 2009 and 2010). This method is important because it provides vital information of working locations throughout the earthwork operations, with the aim of reducing the dependency on the subjective decisions. The correct working locations and timing assist construction managers and planners in resource planning, mobilisation of heavy equipment at require locations and controlling site progress more effectively from location aspects. The linear scheduling methods, however, do not provide exact information of working locations and time throughout the earthwork construction.

Kenley and Seppanen (2009) pointed out that there are mainly two types of scheduling methodologies; an activity-based and a location-based methodology. The location-based methodology is also sub-divided into two types: unit-production and location-production scheduling. It is known as an alternative methodology, which is based on tracking the continuity of crews working on production tasks. DynaRoad (2006) developed commercial software for a construction schedule and controlling the earthwork activities in linear projects. This provides the location-based scheduling information for a whole section but lacks to provide weekly information of locations. TILOS, which is time-location planning software for managing linear construction projects, assist in visualising the repetitive tasks from location aspects. It also provides the flow of scheduling data in terms of time and location on a construction plan (TILOS, 2009). However, existing time-distance charts, produced by DynaRoad and TILOS do not provide weekly information of locations.

This is imperative for effective planning of resources and reducing the space conflicts at construction sites. Consequently, construction mangers depend on the subjective decision for earthwork scheduling due to the limited information of the working locations. Taking into account previous studies, it is concluded that location-based scheduling, which is based on the theory of location-based methodology, is an effective way of representing the planning and scheduling information of earthwork activities in road projects. From the reviewed literature, it was established that the existing time-distance chart is incapable of providing scheduling information of locations. Therefore, this research examined a new methodology for the automatic generation of location-based scheduling that is capable of providing the weekly or daily location information of earthworks. The next section discusses a framework of a computer-based prototype.

3. FRAMEWORK OF A PROTOTYPE

A general specification of the framework of prototype is outlined in (Figure 1) taking into account of the findings from the literature and industry review by (Shah and Dawood, 2011). The framework was designed by integrating the road design data, sectional quantities, productivity rates and unit cost of cut/fill sections and arithmetic algorithms in order to generate automatically a location-based schedule of earthwork and visualise the weekly scheduling information from the location aspects. The developed framework has the capability of generating terrain modelling, cut/fill optimisation, weekly progress profiles, and time space plan, cost profiles and cost S-curves of earthwork activities.

This research, however, focused on the experiments with different scenarios at construction site. A case study from road projects, using the developed algorithm in the prototype (Shah et al., 2008) for the automatic generation of location-based schedules of earthworks was utilised. The paper outlines a methodology that aimed to provide the correct information of weekly locations in the cutting and filing activities, particularly in linear projects like roads and railways construction projects. Although the prototype model is capable of generating weekly progress profiles, cost profiles and S-curve, this paper discuss the details of the methodology and algorithms which aids to automatically generate location-based schedules for earthworks and demonstrates of the function with a case study in a road project. The comprehensive explanation of the model component: inputs, processes and outputs are discussed in the next sections.

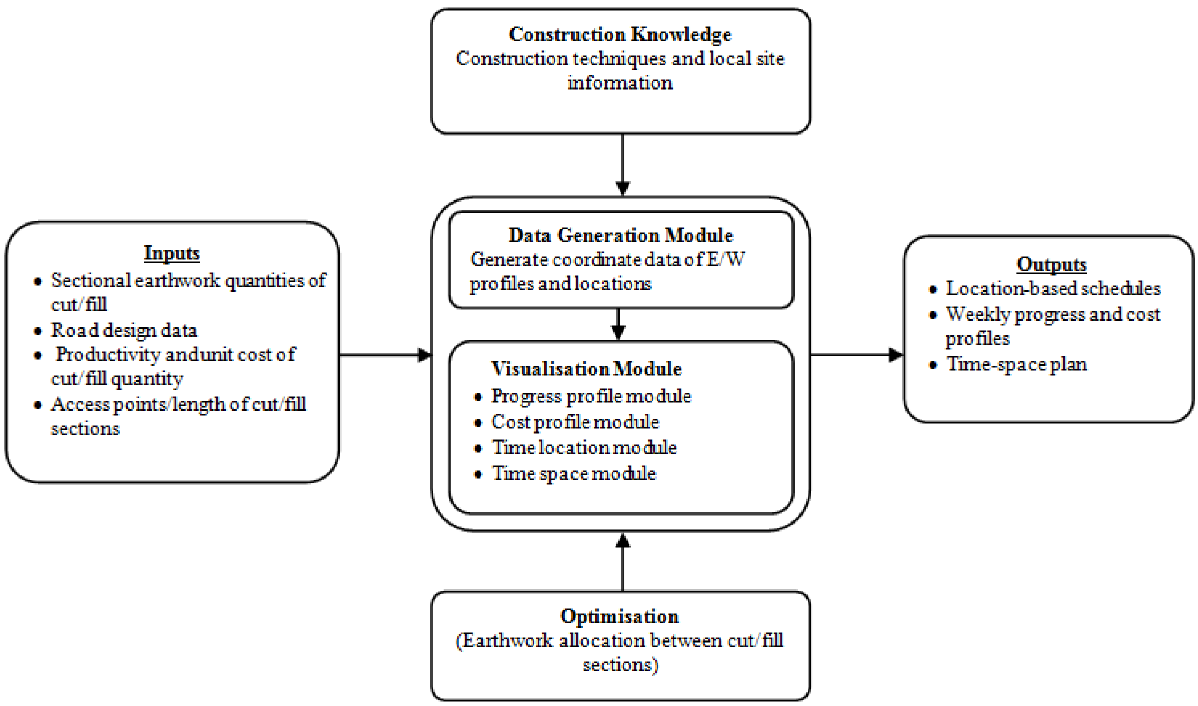


Fig. 1: Framework of a prototype

3.1 Prototype model

This section describes the key components of the prototype model, which includes automatic generation and visualization of location-based earthwork's scheduling information. The sectional quantities of cutting or filling activities, productivity and construction site knowledge base are inputs of the model. The cutting or filling quantity at each station is calculated using road design data including longitudinal section and cross sections. The productivity rate produced by the "RoadSim" simulator is integrated into the model as a main input. The soil characteristics, types of available equipment sets, haulage distance of soil, access road conditions and working efficiency of crew were incorporated within the "RoadSim" simulator. However, earthwork for rock excavation is excluded from this study since the nature of rock excavation is fully different than the normal earthwork operations. The construction knowledge encapsulated from planners and managers was utilized to select the right construction methods under different terrain conditions and soil characteristics considering the available equipment sets for earthworks. The site operational rules and knowledge allow in establishing the sequential relationships amongst listed work activities during the construction operations. The knowledge and operational rules were incorporated within algorithm for the generation of a location-based schedule.

Moreover, an optimization algorithm was also developed and integrated with the model for optimum allocation of earthworks and the movement direction between cuts and fills, borrows to fills or cut to landfills considering economical haulage unit costs. The optimization algorithm is designed by integrating the characteristics of mass haul diagram, unit cost simulated by "RoadSim" simulator, and Excel solver. The solver was built within MS Excel using a Simplex algorithm for linear optimization problems. Before producing a location-base schedule, it is vital to identify the possible sources and destinations of earthwork quantities required for filling and cutting operations in linear projects. The prototype includes four modules as processes: data generation module, visualization module, cost profile module and a time-location module. Data generation module processes the input data to generate the coordinate data of weekly locations of cutting and filling activities incorporating the different productivity rates. The time location module processes the coordinate data and generates location-based schedules for earthwork activities. The next section discusses the generation of location-based scheduling.

3.2 Generation of location-based scheduling

Location-based scheduling is a planning tool, which is widely applicable in earthwork planning tasks. The location-based scheduling is also known as time-distance planning, time-chainage planning and linear scheduling method. It enables the design and display of planning and scheduling information of earthwork activities in two dimensions: Location in X-axis and Time in Y-axis or vice versa together with topographical information of a road project. The slope of activities displayed in time location chart represents a rate of production of the earthwork activities. If the slopes of planned activities are compared with the slope of actual activities, they provide visual information of early indication regarding possible of conflicts or overlap between activities during the course of activity progress.

The proposed innovative methodology is capable to identify the starting and ending location as well as start and end period of cutting and filling activities at planning stage and the actual information of weekly locations assist to planners for efficient resources planning. The methodology is designed with an arithmetical algorithm that identify the locations (stations) along a road section which are broken down into weekly or daily schedules satisfying the linearity characteristics (start and end locations having equal production rate) of the earthwork activities. The equation 7 developed by Shah et al., 2008, is being used for identification of station number at each layer during earthwork operations by incorporating the 'variable' productivity data.

$$V_r = [\{\sum_{i=1}^{i=n} (V_i) - P\}/n] \qquad (7)$$

This process is repeated at each layer of cutting or filling sections to achieve the remaining volume (Vr) at each station is equivalent to zero (at the design level of road) at the selected working sections along a road project. At each layer, the starting and ending stations are identified and their lengths between the two stations are determined by the algorithm, designed in the model with help of VBA programming language. These lengths, at each layer between working stations, increase from the first to the last layer at both cutting and filling sections of the earthwork operation. Similarly, cutting and filling sections are selected according to the earthwork schedule to complete the earthwork operations throughout the construction of a road section. If the cutting or filling sections are longer, these sections are divided into manageable sections and the processes above are repeated to achieve the design level of the road.

In this model, two input variables: Productivity (P) of earthwork activities produced by "RoadSim" and working length (X) determined by "mass haul diagram" were integrated with the model to search the coordinate of starting and ending locations of working section. The algorithm assists to calculate the coordinate of working locations considering "variable" productivity data throughout the construction operations in a road project. Therefore, coordinates of weekly or daily locations directly depends on the value and unit of productivity i.e. weekly or daily productivity by assuming 40 hours per week or 8 hours per day as standard working time. The identified coordinate data of locations and time of earthwork activities are stored in a table at first and then exported the coordinate data by programme to generate location-based scheduling. The location-based scheduling has generated automatically. The automatic generated location-based schedule, which is key outputs of the model, provides more accurate information of working locations for earthwork scheduling on a weekly and daily basis. The location-based schedule assists to planners and construction managers in allowing the visualisation and analysis of the status of construction activities on a particular location along the road sections. The next section describes the visual function of the model that assist to planning in visualising the information about weekly locations and space congestion in earthwork operations.

3.3 Visualization of scheduling information

This section presents the development of a visualization component of the prototype model. This provides the visual information of earthwork scheduling, space congestion, progress profiles, and communicates the construction process sequences with consideration given to location aspects. The Visualization Module (VM) processes the coordinate data of location-based schedules and transforms them into a visual format to visualize earthwork scheduling information. The VM was developed using the C# and VBA programming language on MS Excel platform. The required input data was stored in MS Excel worksheets and used as database. Several VBA macros were developed to process input data and generate automatically into visual outputs of the model. The VM imports data using Structured Query Language (SQL) inquiry, and transforms the imported data into a visual representation in tabular and graphical information.

A snapshot of the visual outputs of the model is shown in (Figure 2), which includes weekly progress and cost profiles, cost S-curve, location-based earthwork scheduling information and time-space congestion plan. The location-based plan provides information related to the congested locations and pavement activities such as sub-base, base course and top surfacing tasks (see Figure 2). The visualization component also provides tabular information of starting and ending locations on weekly basis throughout the construction operations of earthworks and pavement. The following section describes a case study experiment to evaluate the model's functions (automatic generation and visualization of location-bases scheduling information of earthworks) using a real life data from road project.

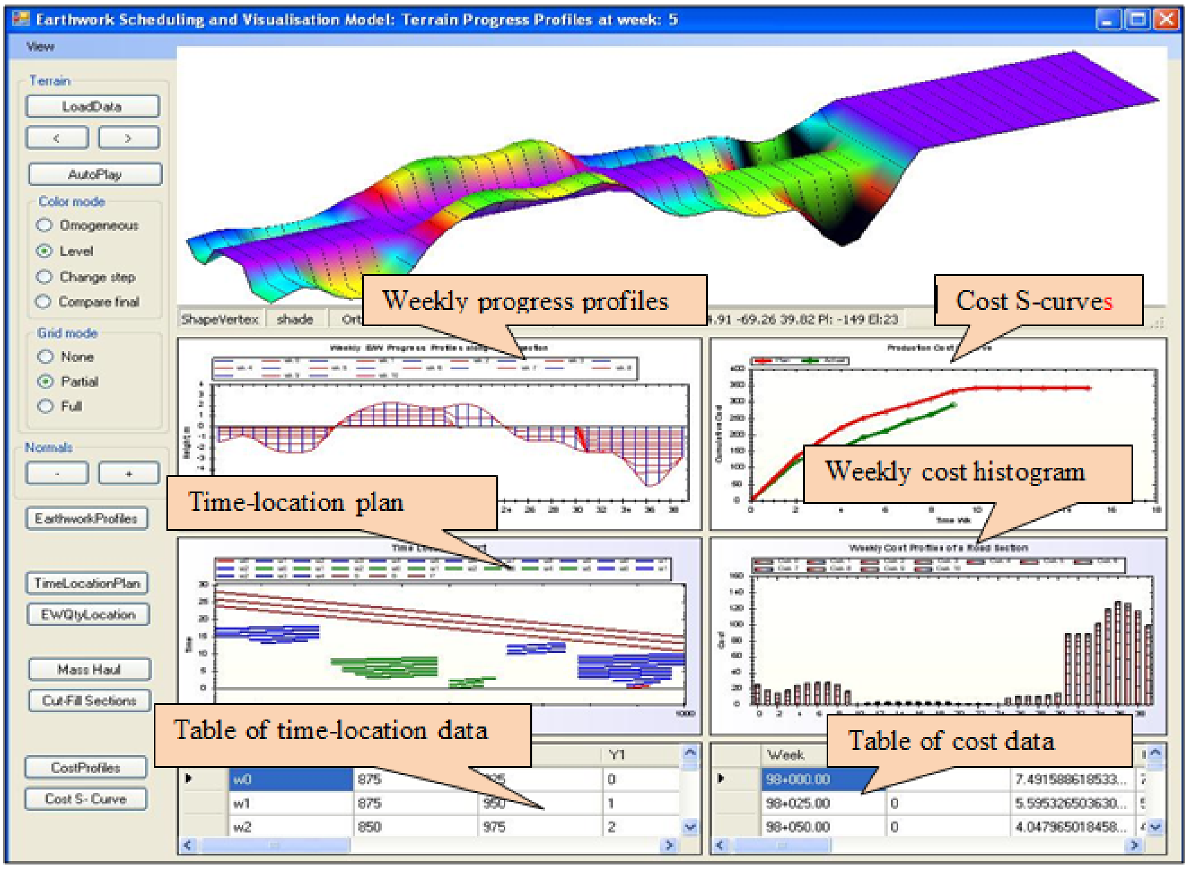


Fig. 2: Snapshot of the visual outputs of the model

4. A CASE STUDY EXPERIMENT

A case study involving 1.0 kilometer of road section of lot no. 3 road project in Portugal was selected to demonstrate the functionalities of the model. Actual road design data including L-section and X-section is considered, and the sectional quantity of earthwork is calculated assuming typical trapezoidal section at 25 meter intervals along the selected road section. The productivity data of cutting or filling activities is considered as a key factor that affects the construction duration, working locations and numbers of construction layers required to complete earthwork operations. Since the model outputs directly depend on the accuracy of the productivity data, the case study was run to compare the variation in the productivity value between actual site progress and model used value for earthwork activity. The case study results revealed that the actual productivity value was lower by 2 percent compare to the productivity value produced by the model to generate a location-based schedule for earthwork activity in road projects. The outputs of the model are: automatic generation of earthwork progress profiles, 4D terrain surfaces, cost profile, production S-curve and location-based schedules for earthwork planning and visualisation of scheduling information from the location aspects.

4.1 Experiments under different options in a road section

A road section having 4-cut and 5-fill sections was selected as a case study to demonstrate the model functionality of automatic generation of location-based schedules /time-location plans considering different site conditions, site access points and with construction sequences. The time-location plans produced by the model are presented below. A total of 18 weeks was required to complete earthwork operations for the selected road section when one equipment set for both cut and fill sections was mobilised assuming with a production rate of 6671 m^3/wk considering the 30 hrs per week as working time. The productivity was calculated using "RoadSim" simulator (Castro and Dawood, 2009), assuming a suitable set of equipment, soil characteristics and site constraints for the selected road section in the case study. A total of 7 different options considering under different site conditions and construction sequences were included in the experiment aimed with to evaluate the model function of automatic generation of location-based earthwork schedules or time-location plans.

4.1.1 Option 1: Construction sequences (C1-C4 and F1-F5)

In this option, the construction sequences of cut and fill sections were selected from C1 to C4 and F1 to F5 as shown in Figure 3. The earthwork operations included fill from cut with one set of cutting and filling construction equipment. The construction operation was performed from the start to finish stations in the forward direction. The direction of earthwork quantities (m^3) allocation between cut and fill section is shown in road profile with arrow diagram and the construction sequences of cut-fill operations are shown in time-location plan (Figure 4). Similarly, other options (2 to 7) are considered under different construction sequences between cut-fill sections including borrow pits for a selected road section.

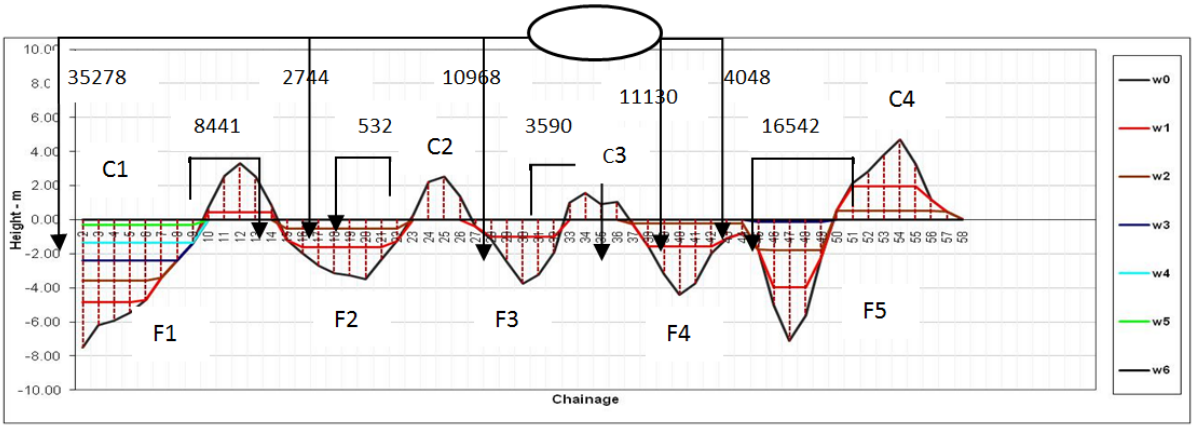


Fig. 3: Road section showing 4-cut and 5-fill sections with optimised earthwork quantities

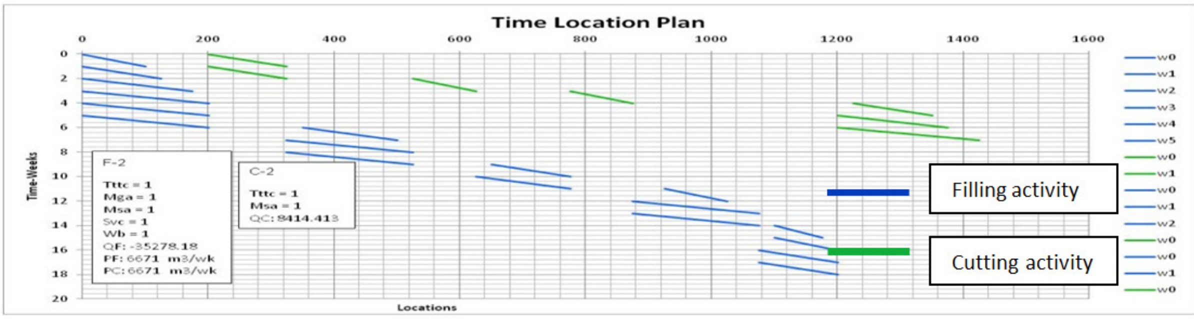


Fig. 4: Time-location plan of a road section generated by the prototype with option-1

4.1.2 Option 2: Construction sequences (C4-C2 and F5-F1)

In this option, the construction sequences of the cut and fill sections shown in Figure 3 above were selected starting from C4 to C1 and F5 to F1 with one set of construction equipment. The construction operations were performed from finish to start in a backward direction. The time-location plan generated by the model considering option 2 is shown in Figure 5.

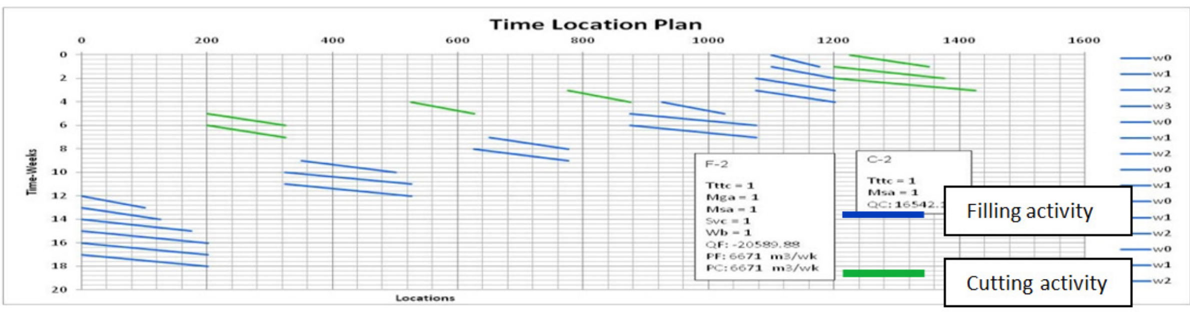


Fig. 5: Time-location plan generated by the prototype model with option 2

4.1.3 Option 3: Construction sequences (C4-C1 and F1-F5)

In this option, the construction sequences of the cut and fill sections shown in Figure 3 were selected from C4 to C1 and from F1 to F5 with one set of construction equipment. The cutting operation was performed from finish to start of a road section in the backward direction and filing operations starts from start to end in the forward direction. The time-location plan generated by the model considering option 3 is shown in Figure 6.

Fig. 6: Time-location plan generated by the prototype model with option 3

4.1.4 Option 4: Construction sequences (C1-C4 and F5-F1)

In this option, the construction sequences of cut and fill sections shown in Figure 3 were selected from C4 to C1 and F1 to F5 with one set of construction equipment. The cutting operation performs from start to finish in the forward direction and filing operations starts from finish to start backward direction. The time-location plan generated by the model considering option 4 is shown in Figure 7.

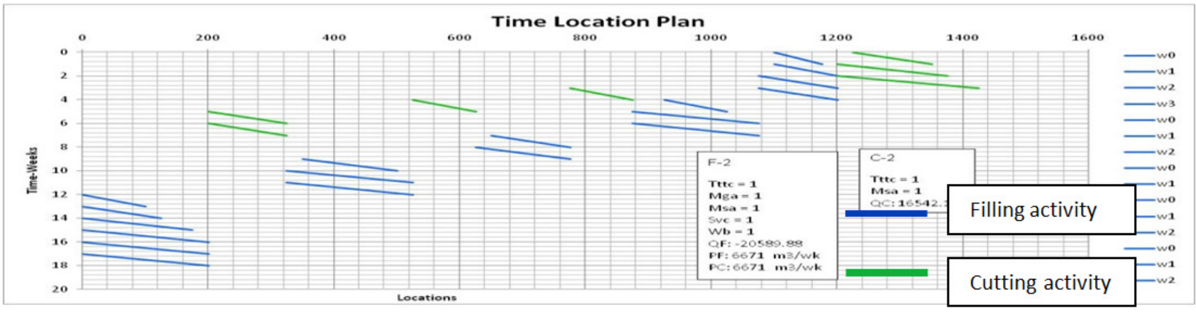


Fig. 7: Time location plan generated by the prototype model with option 4

4.1.5 Option 5: Considering obstruction at point A (at chainage 0+625)

In this option, the construction sequences of cut and fill sections shown in Figure 3 were selected from C1 to C4 and from F1 to F5 with two set of construction equipment. One set of equipment at the start of the road section and second set is at station (0+625m) due to an obstruction at point A. The time-location plan generated by the model considering option 5 is shown in Figure 8.

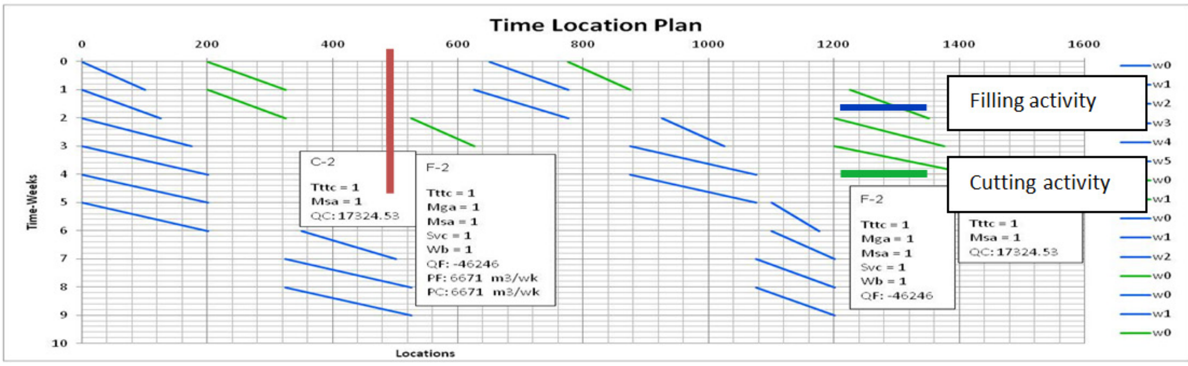


Fig. 8: Time-location plan generated by the prototype model with option 5

4.1.6 Option 6: Time location with daily productivity (1779 m^3/day)

In this option, the construction sequences of the cut and fill sections were selected from C1 to C4 and from F1 to F5 with two sets of equipment but the time location plan was generated on a daily basis. The time-location plan produced by the model under option 6 is shown in Figure 9. The time location plan showed a total duration of 30days @ 1779 m^3/day with 8 hrs/day and two sets of equipment.

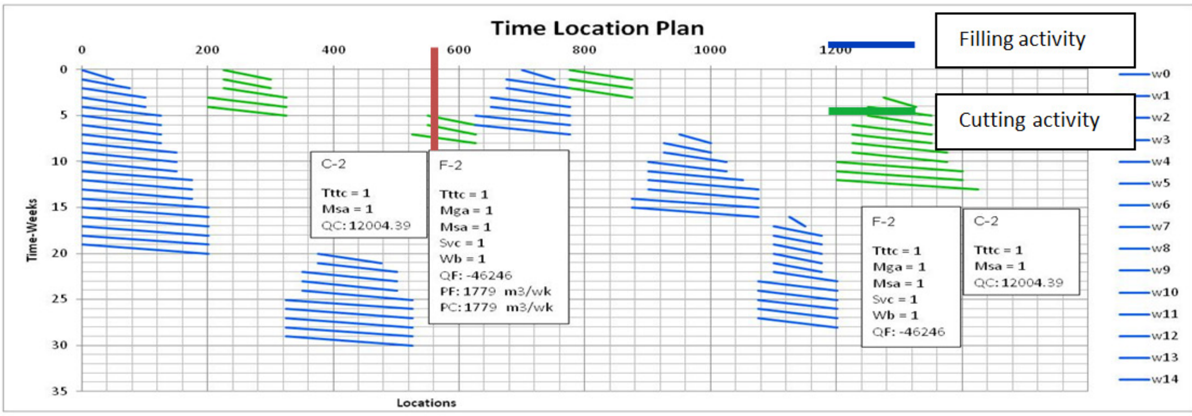


Fig. 9: Time-location plan generated by the prototype model with option 6

4.1.7 Optiom 7: Time-location plan with space congestion

In this option, the construction sequences of cut and fill sections were selected from C1 to C4 and from F1 to F5 with one set of equipment. The congestion location is shown in red in the plan at first week of fill section 5 only. The time-location/space congestion plan generated by model under option 7 is shown in Figure 10.

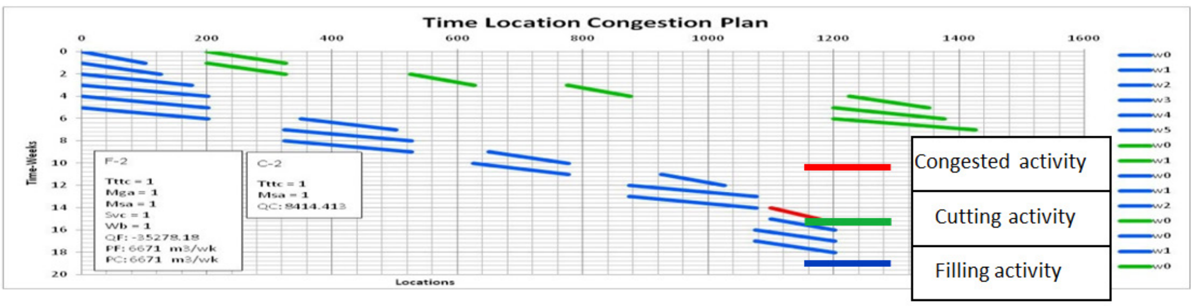


Fig. 10: Time-location congestion plan generated by the model under option 7

4.2 Comparison between company used and model generated location-based schedules

A 7 kilometre road section was selected with the assistance of a company (Mota-Engil) for the validation of the time–location plan (location-based scheduling) produced by prototype model. The duration of earthworks shown in a time–location plan provided by the company was compared with the duration shown in the time–location plan generated by the prototype model. The comparative results including detailed information of weekly working lengths/locations of a road section, earthwork quantities, productivity, and total duration of the earthworks are presented in Table 1.

Table 1: Comparison of between company-provided and model-generated time-location plan

S. N.	Road Chainage	Sectional Length (m)	E/W Quantity (m3)	Cut/Fill Activity	Production Rate m^3/wk	Company-produced Results		Model-generated Results		Variation
						Time (wk)	Locations	Time (wk)	Locations	Time %
1	0+000 -	925			2309		0+000		Table 1 of	
2	0+925 -	1750			3464		0+925 &		Table 2 of	
3	2+675 -	925			5196		2+675 &		Table 3 of	
4	3+600 -	3400			10392		3+600 &		Table 4 of	

The comparison results (presented in Table 1) show that model simulated production duration of earthworks is higher by 8.7 per cent (average) than the company estimated production duration of earthwork for both cutting and filling operations. The duration was calculated by rounding the values for each cut/fill section in case of the model-generated schedule, whereas, the duration was calculated by dividing whole quantities with productivity (production rate) of earthworks for each section in case of the company produced schedule (Table 1). Figure 11 represents a time-location plan/location-based schedule of a road project in Portugal, produced and utilised by the company. The plan was produced by dividing the road section into four sub-sections (0+000 to 0+925, 0+925 to 2+675, 2+675 to 3+600 and 3+600 to 7+000). Each section was planned with different sets of equipment separately at different production rates (Table 1).

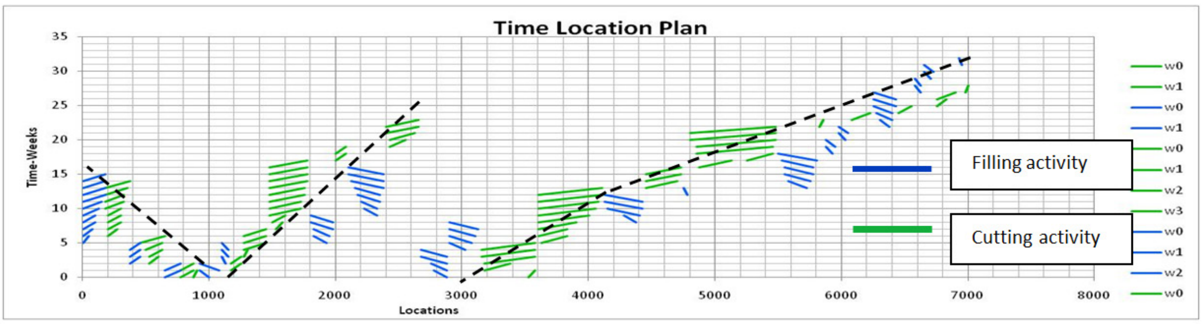


Fig. 11: Colour lines model generated and the dotted lines represent company-produced time-location plans

Additionally, several experiments were carried out at the earthwork construction site in a road project of lot no 5 in Portugal by Mota-Engil. The experiments revealed that the actual production time was 2.34 per cent lower than the model-simulated production time of earthworks because the delay in variation of soil characteristics at the cutting section. Hence, it was concluded the model produced location-based schedules that are widely acceptable for earthwork operations in road construction projects. Therefore, this should result in improved resource planning including mobilising construction equipment for earthworks from a location viewpoint.

5. CONCLUSIONS

The present study was designed to present a new methodology with a prototype model that generates automatically location-based schedules. One of the significant findings to emerge from this study is that existing linear schedules do not provide the correct information of weekly locations of work activities in linear projects. A framework and a prototype model with detailed specifications were developed by integrating different factors that affect linear schedule, such as the road design data, sectional quantities, productivity rates and unit cost of cut/fill sections and arithmetic algorithms. The algorithm, underpinned within the model assist to generate the weekly coordinates of working locations on a daily or weekly basis by incorporating different productivity rates and site constraints in earthworks. The model has capability to generate automatically weekly progress profiles, space congestion plan of earthwork operations in linear projects. A case study using data from road projects was used to demonstrate the functions of the model. An experiment was run to analyse the model generation capability of location–based earthwork schedules under different options of construction sequences and sets of construction equipment. These options include different sequences of cut-fill section in forward/backward directions, site access points, and different productivity rates. The experiment results revealed that the model provides weekly information of working locations and required resources including materials, equipment and crew in earthwork operations. The model was also evaluated from road construction experts and they suggested that it is a very useful tool in supporting the initial strategic decisions at the planning stage and provides the scheduling information more effectively from the location aspects. Running various strategies with the model would allow optimisation of resources, including construction equipment useful in the earthwork operations.

This study has found that the model-generated location-based schedules are satisfactory for practical applications as a location-based scheduling tool in earthwork operations in linear construction projects like roads or railways. The space congestion plan was also found as a valuable tool for decision-making in avoiding space congestion and the equipment being idle. The paper concluded that the model is a valuable decision support tool that assists construction manager in mobilising construction equipment and visualising scheduling information from locations aspects. The tool is also helpful in assisting the efficient resource scheduling, progress monitoring from location aspects, reducing space conflicts and communicating the scheduling information more effectively from the location aspects in earthworks construction.

6. REFERENCES

Ahmed, F. W. and Walid, Y. T. (2002) A Virtual Construction Environment for preconstruction planning. *Automation in Construction* 12: 139-154.

Arditi, D., Tokdemir, B. O. and Suh, K. (2001) Effect of learning on line-of-balance scheduling. *International Journal of Project Management* 19: 265-277.

Arditi, D., Tokdemir, B. O. and Suh, K. (2002) Challenging in Line-of-Balance Scheduling. *Journal of Construction Engineering and Management* 128(6): 545-556

Askew, W. H., Al-Jibouri, S. H., Mawdesley, M. J. and Patterson, D. E. (2002) Planning linear construction projects: automated method for the generation of earthwork activities. *Automation in Construction* 11: 643 – 653.

Castro, S. (2005) Integrated simulation models applied to road construction management. *PhD Thesis*, University of Teesside, UK.

Castro, S. and Dawood, N. (2009) Automating road construction planning with a specific-domain simulation system. *Journal of Information Technology in Construction* 14: 556-573.

DynaRoad (2006), DynaRoad: plan, schedule and control [Online]. Available at: http://www.dynaroad.fi/pages/index.php [Accessed 25 May 2013]

Garold, D. O., Samir, A. A. and Gregory, A. D. (2005) Linear scheduling of highway project. Oklahoma Transportation Centre Research Projects, OTC-25.

Harmelink, D. J. and Yamin, R. A. (2000), Development and application of linear scheduling techniques to highways construction projects, Technical report of FHWA/IN/JTRP-2000/21: 8-69.

Johnston, D. W. (1981) Linear Scheduling Method for Highway Construction. *Journal of Construction Division*, ASCE 107 (2): 247-261.

Kenley, R. and Seppanen, O. (2009) Location based management of construction projects: part of a new typology for project scheduling methodologies. *Proceedings of the 2009 winter simulation conference* 2563-2570, Dec 13-16, Austin, Texas, USA.

Kenley, R. and Seppanen, O. (2010), Location based management for construction projects: planning, scheduling and control, 1st ed., Spon Press, UK.

Kim, S. and Russell, J. S. (2003) Framework for an intelligent earthwork system Part I system architecture. *Automation in Construction* 12: 1-13.

Koskela, L. (2000) An exploration towards a production theory and its application to construction. *PhD Thesis*, VTT Publications.

Mattila, K. G. and Abraham, D. M. (1998) Linear scheduling: past research efforts and future directions. *Engineering, Construction and Architectural Management* 5 (3): 294-303.

Mawdesley, M. J., Askew, W. H. and Al-Jibouri, S. H. (2004) Site layout for earthworks in road projects, Journal of *Engineering Construction and Architectural Management*, 11(2): 83-89.

Shah, R. K. and Dawood, N. (2011) An innovative approach for generation of a time-location plan in road construction projects. *Journal of Construction Management and Economics* 29(5): 435-448

Shah, R. K., Dawood, N. and Castro, S. (2008), Automatic Generation of Progress Profiles for Earthwork Operations using 4D Visualisation Model. *Journal of Information Technology in Construction* 13: 491-506.

TILOS (2009) Linear Project: TILOS [online]. Available at: http://www.tilos.org/software_en.html (Accessed 15 May 2013).

ROAD CONSTRUCTION PROJECTS: AN INTEGRATED AND INTERACTIVE VISUAL TOOL FOR PLANNING EARTHWORK OPERATIONS

Mohamad Kassem, Rajiv Chavada & Nashwan Dawood
Teesside University, UK

Claudio Benghi
Northumbria University, UK

Romeu Sanches
Mota-Engil, Portugal

ABSTRACT: *Road construction projects are expensive and highly affected by uncertainties related to factors such as weather, type of soil and other site and environmental factors. These uncertainties impact on the accuracy of predicting resource productivity and developing reliable schedules for earthwork operations. Current simulation and planning approaches and tools not only lack the capabilities of dealing with such uncertainties but they also lack the integration and intelligence to simulate multiple strategies – a model should be built every time a new scenario is required. As a result, planning decisions regarding the assignment of resources are purely based on planners experience and project plans are not the outcomes of comparing various allocation strategies.*

This paper proposed an approach which is visual, interactive, and integrator of the functions involved in earthwork operation such as activity scheduling, resource productivity calculation, optimal distance calculation and profile visualization. This specifically addresses the challenges related to the limited intelligence and capability of simulating multiple strategies of resource allocation in earthwork operation. The proposed development builds upon a prior study (Castro and Dawood, 2005) that developed a knowledge-driven approach to tackle the 'uncertainty' challenge affecting the productivity of resources. This paper hypothesizes that an integrated approach which integrates the various functions involved in earthwork operations and provides an interactive environment where planners could easily change planning decisions and promptly analyze the effect of their decisions could improve the reliability of plans and consequently improve the performance of road construction projects.

KEYWORDS: *Earthwork* operations, interactivity, resource planning, visualisation.

1. INTRODUCTION

Road construction projects are inherently unpredictable and complex due to the dynamic nature of site operations and uncertainties related to weather, soil characteristic and site conditions. Current practices suggest that project planners carry out earthwork operations in road construction using deterministic methods based on their past experience and knowledge. As a result, cost and time overruns are often caused by the lack of inclusion and appreciation of risk factors. Although information technology (IT) systems can demonstrate uncertain and stochastic behaviour of different processes to predict the outcomes of construction projects, IT systems utilised in earthwork operation still lack such capabilities.

There have been several studies addressing the above challenges. Jayawardane and Price (1994) developed RESOM (Roadwork Earthwork moving Simulation Optimisation Model) to optimise earthwork operations applying linear/integer programming techniques. Askew et al. (2002) used mass haul diagram (MHD) techniques for earthwork allocation between cutting and filling sections. MHS is graphical representation of the volume of cutting and filling sections in relation to their position on the site, and are widely used for linear construction like road and railways (Warren, 1996, p85). Liapi (2003) a collaborative decision-making construction scheduling and planning for highway construction projects in which visualisation is utilised to validate the construction

---

Citation: Kassem, M., Chavada, R., Dawood, N., Benghi, C. & Sanches, R. (2013). Road construction projects: an integrated and interactive visual tool for planning earthwork operations. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

process. Kemppainen et al. (2004) developed a system dubbed "Dyanroad2", which is a mass haul and schedule planning and control software, to support planners optimising the cost of resources, mass hauls and schedules. Dyanroad2 encapsulated linear and genetic algorithms for its optimization functions. Kang et al. (2006) used morphing (visual) techniques to simulate earthwork operations such as cutting and filling where progress of site activities are simulated and changes of ground levels due to cut and fill are visualised. Chi-Ming et. al. (2007) developed an integrated system that combines a path-finding algorithm: ripple ring, plant database and genetic algorithms for optimising the feasible alternatives. Kenley and Seppanen (2009) developed activity and located based scheduling methodologies for managing the construction sites. Shah and Dawood (2011) developed a model that produces weekly location plans presented in the form of time-chainage. The time-chainage diagram is also known as Linear Scheduling Method (LSM)/Time-location charts, and it is widely used in those linear construction projects that have a repetitive nature of work activities (Kenley, 2004).

There are some commercially available tools for earthwork planning. The main two tools are TILOS[2] and DynaRoad[3]. TILOS is a time-location planning tool for managing linear construction projects such as roads, rail lines, pipelines and tunnels. DynaRoad[4] is a tool that can be used for schedule, mass haulage optimisation and progress control of earthwork operations in construction projects such as roads and railways. However both tools lack the capabilities of simulating the productivity and cost while considering factors and variables such as sets of equipment, site constraints and soil characteristics and enabling "what if scenarios".

The development proposed in this paper is a continuation of a previous research effort by Dawood and Castro (2009). They have developed a knowledge-based simulator dubbed RoadSIM to assist planners select resources and develop reliable project plan. Also with this approach, implementing what-if analysis is not possible due to the lack of integration between the functions of earthwork operations and the lack of interactivity. The approach proposed in this study is to integrate the knowledge driven resource module (i.e. RoadSIM) with the other earthwork functions including project planning and scheduling, optimal distance calculation and profile generation in an interactive visual tool. It is hypothesised that such integration augmented with visualization and interactivity could lead to increase the reliability of construction plans. To achieve the proposed approach, the paper addresses the below three objectives:

- Develop a conceptual approach that identifies and integrates the different earthwork components including resource module, activity planning module, distance optimisation and earthwork profile visualisation.
- Implement the different earthwork modules into an integrated, visual and interactive environment using object oriented methodology.
- Verify the system developed with empirical industrial data.

2. THE CONCEPTUAL APPROACH

The conceptual approach for integrating the different functions of earthwork operations and enabling a visual interactive planning is depicted in Figure 1. It includes the data input layer, the process layer and the outcome layers. The approach integrates: the resource module, profile visualisation, optimal distance calculation and activity planning and scheduling in an interactive, visual and inter-dependent manner. Information can be exchanged systematically between the different functions. Using such a approach, project planners can avoid the execution and assignment of under-allocated or over-allocated resources and therefore, improve the productivity at operational phase. Earthwork operations have predefined resources and their duration is calculated through productivity rates. The system demonstrates an interactive profile viewer for "Mass-haul" and "Time-distance" profiles, resource model for productivities calculation, Gantt viewer for activity planning and management. As a result of such inter-dependent integration, what-if scenarios can be immediately performed. Each of the system layers is described below.

---

2 TILOS (2013), Available at: [http://www.tilos.org]

3 TILOS (2013), Available at: [http://www.tilos.org]

4 DynaRoad (2010), Available at: [http://www.dynaroad.com]

2.1 System Input

The input layer contains information and empirical data about the productivity of resources collected from numerous historical sites. There are two types of system inputs: resource information stored in a resource knowledgebase database and earthwork profile data. The resource information consists of empirical site experience and knowledge about the productivity and efficiency of equipment data productivity utilized in different earthwork operations such as cutting-filling. Such information is also linked to the empirical values of factors that affect resource productivity such as soil type and characteristics and operational factors such as haul distance. The modelling of relationships between resource productivity and such variables can be found in Dawood and Castro (2009). The earthwork profile data (i.e. chainage distance, volume-quantity information, actual and design ground levels) are user input data specific to the new project. To reduce the complexity of earthwork operations where resources interact with each other during the execution of site activities, the "atomic model" concept was introduced (Dawood and Castro, 2009). The next section introduces the concept and demonstrated it with an example.

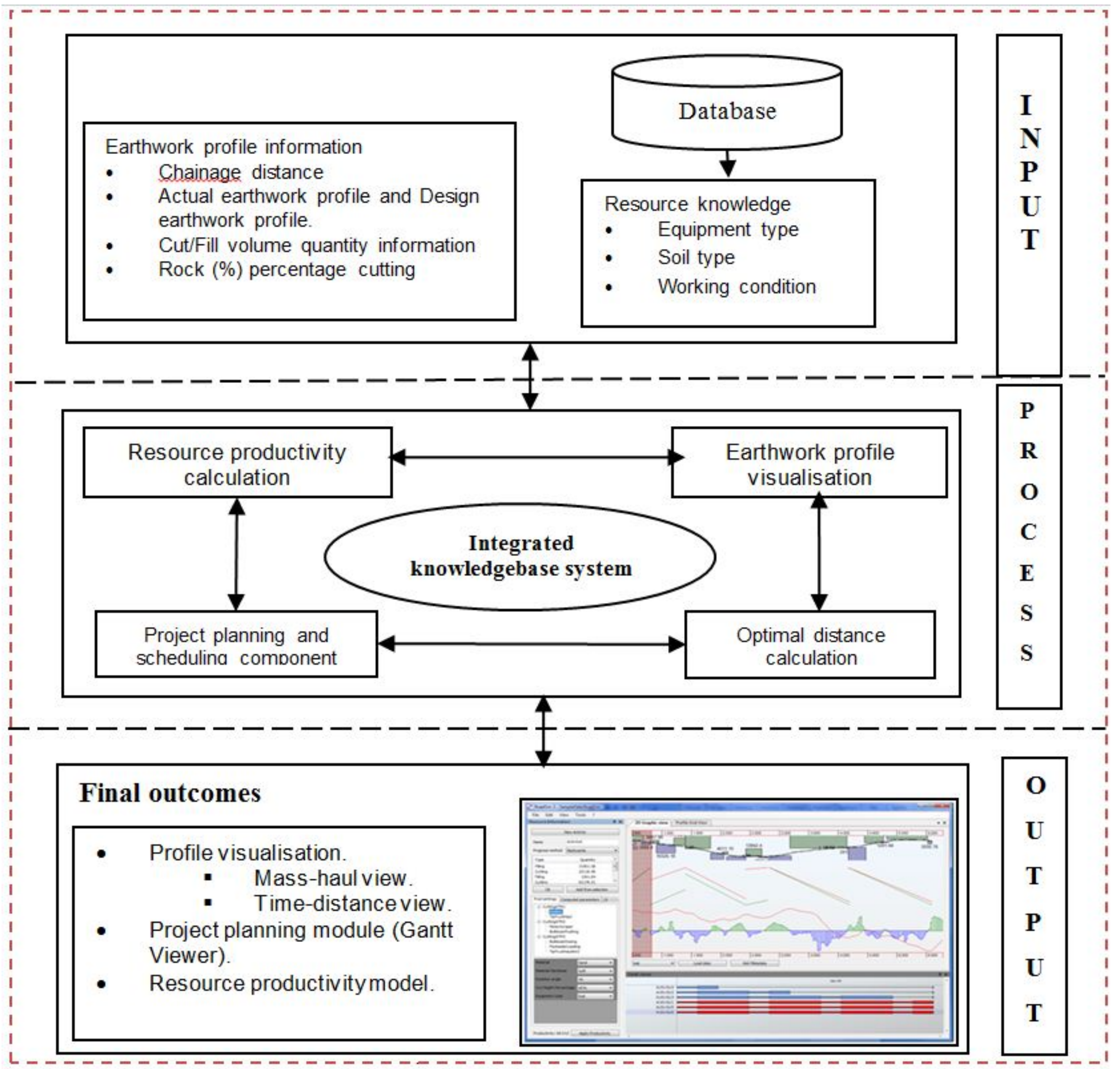


Fig. 6: The different layer of the proposed approach

2.1.1 Atomic Models

An atomic model refers to the involvement of the number of equipment units which can be used to perform an activity, such as cutting or filling, in earthwork operations. In order to reduce the complexity of earthwork operations, atomic models cluster equipment into sets that are required to perform site operations. Atomic models use empirical information built using interviews to elicit knowledge from construction managers (Castro and Dawood, 2005). They map the value stream to minimize unnecessary execution of resources during the execution phase. Using this information, project planners can carry out different what-if scenarios to facilitate the selection of resources. Two examples of atomic models are presented in figure 2 for two site operations:

- ***Excavation operation***- Excavate the soil mass using excavation equipment
- ***Tipper truck Hauling-*** Haul the excavated soil to a specific distance using tipper truck

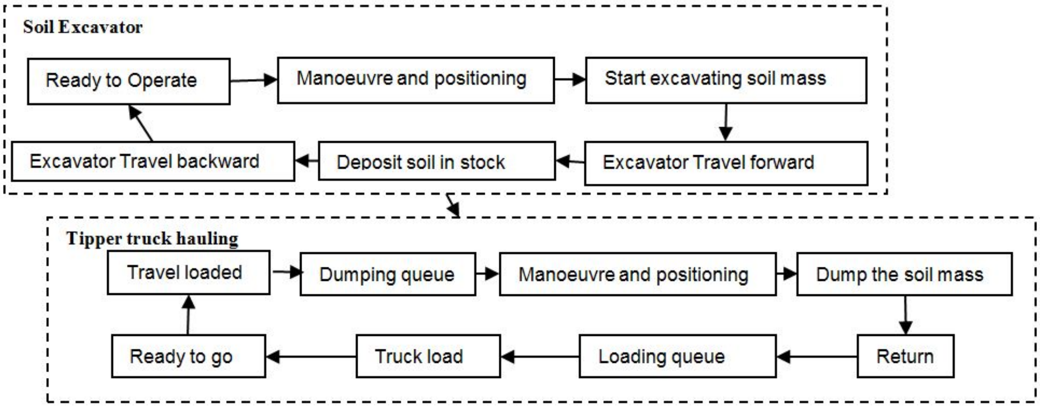


Fig. 7: Atomic model for Cutting operation

2.2 System Processes

The process layer is the core of the system where the different earthwork functions for earthwork operations (i.e. profile visualisation, resource productivity calculation, optimal distance calculation and project resource planning) are integrated. The different functions are explained below:

2.2.1 Profile visualization

This function the user input of earthwork profile data and provides the visualisation in both graphical and tabular formats. It is an interactive component that visualises customized earthwork profile information into mass-haul and time-distance visualisation profile. Mass-haul profile visualises cutting and filling volume quantities along with Bruckner curve (Bruckner Mass haul curve profile). Planners can interactively select earthwork volume to calculate cutting/filling quantities and assign resources (team and equipment) on a specific chainage distance. Time-distance profile shows an earthwork profile along a chainage distance versus activity progress direction and time. It demonstrates a specific activity (duration is presented in weeks) that will be carried out on a chainage distance. The system can also interactively demonstrate activity progress into “forward” and “backward” direction (figure 3). Figure 3 shows the Bruckner Mass haul curve profile, the actual and design curve profile and a global view along with distance chainage.

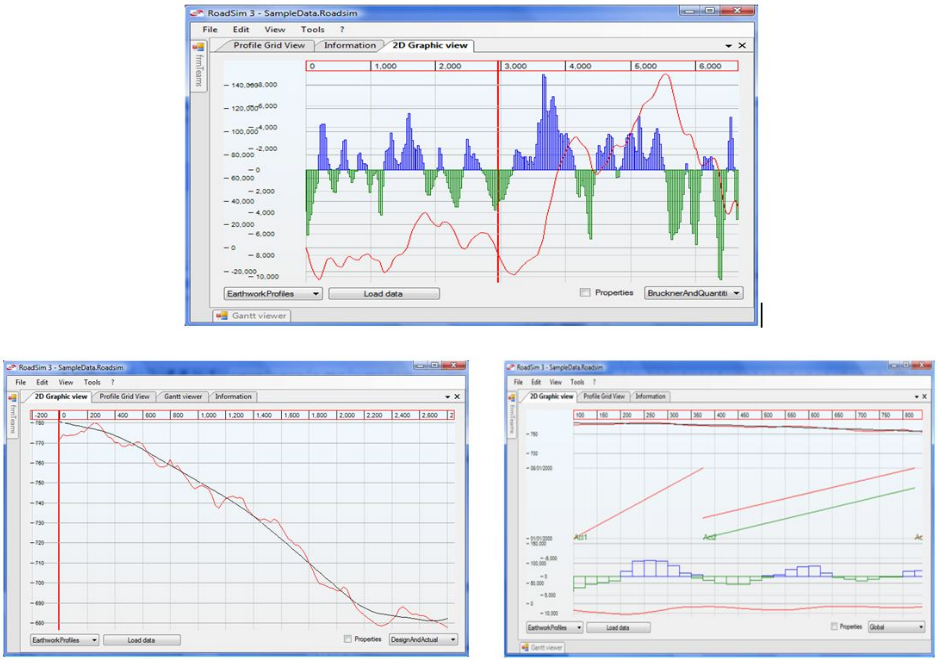


Fig. 8: Earthwork profiles visualisation

2.2.2 Resource productivity calculation

The productivity formulas considered all factors affecting the productivity including site operation type, working conditions, resource availability, site constraints, soil characteristics and other external factors. Such formulas for the calculation of equipment productivity have been developed in RoadSIM by Dawood and Castro (2009). The productivity of each earthwork activity is calculated once the atomic models, their levels and resource involved in that activity have been determined. Then, the productivity is calculated as the sum of the product between the atomic models of the resources intervening in the activity and the coefficient expressing the working condition of resources (figure 4).

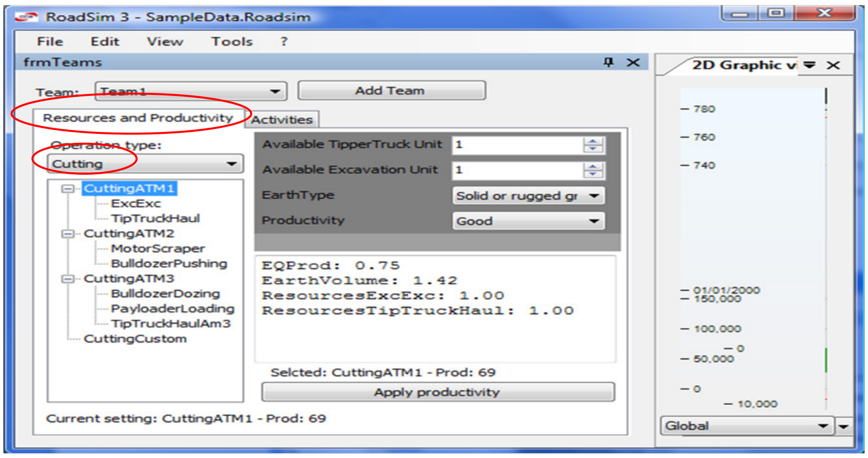


Fig. 9: Productivity Calculation

2.2.3 Optimal distance computation

Mass-haul distance optimisation was achieved using a linear optimisation technique which minimises wastes (i.e. borrow pit and land-fill section) and maximizes the utilization of resources. The simplex algorithm has been implemented as a linear optimisation method to balance mass quantities and optimal distance. This algorithm has been developed in C#.Net by using LPSolve open source library.

2.2.4 Project planning and scheduling

The critical path method (CPM) was implemented in the proposed system as a method for scheduling project activities. The Gantt char was utilised to visually represent the project plan. The “Gantt-viewer” assists planners to organize a list of weekly earthwork activities and interactively analyse sequence of project activities. In addition, this component has project management capabilities. For example, planners can change activity start and finish dates and the network logic (i.e. predecessor and successor relationship) if required. The component is linked to the other system components to allow a dynamic project planning and what-if scenarios. For example, activity duration depends upon the selection of the resources for mass-haulage. If the atomic model changes, the resource involved in the atomic model change, the productivity will and affect the total activity duration. As a result of such integration and interactive visual capabilities, the proposed approach and tool can be considered as powerful project management engine for earthwork operation (figure 5).

2.3 Outputs of the System

The aim of the proposed study was to develop a more sophisticated approach compared to those proposed in previous studies and commercial tools by integrating the various functionalities involved in earthwork operations in an integrated, interactive and knowledge driven system. The integration involved processes relating to project planning, resource productivity calculation, optimal distance calculation and visualisation. As a result, the system provides visual, interactive outputs and analytical capabilities that are very valuable for resource planning of earthwork operations (Figure 6). Such capabilities can be used by planners to analyse earthwork volumes and quantities and conduct interactive time location planning by producing mass-haul, time distance, and Bruckner view (Mass-curve) diagrams. The interactive nature of the system allows planners to conduct immediate different what-if scenarios to select the resource that meet the project demand. In addition, one of the system outputs is a Gantt chart viewer that can be used to interactively visualise and analyse the project activities at any date (Figures 5 and 6). The system also visualises road obstruction elements such as bridges, hydraulic passage, entry access point and upper and under passages (Figure 6). The integration of these functionalities and interactive visual with the augmentation of functionalities with optimisation features such as automatic productivity calculation and optimal distance calculation are expected to improve the quality of planning and consequently the productivity and efficiency of road construction sites.

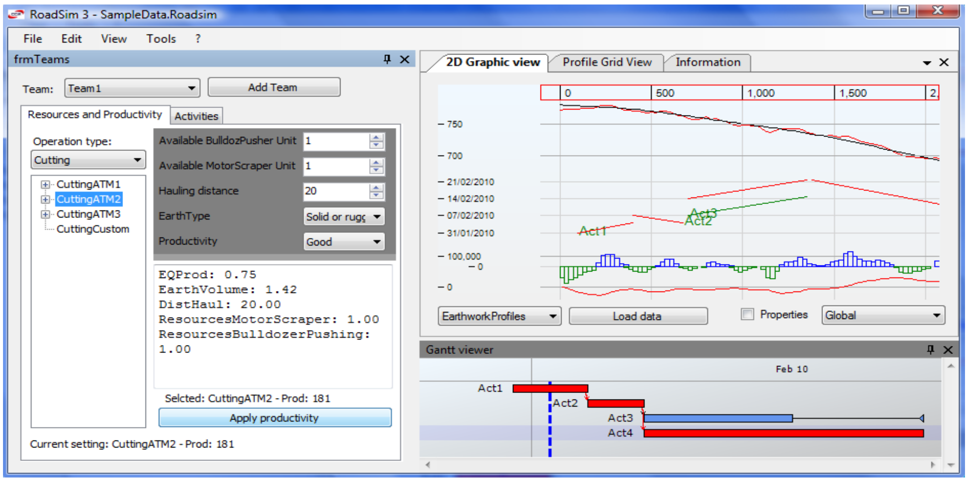


Fig. 10: Project planning and scheduling

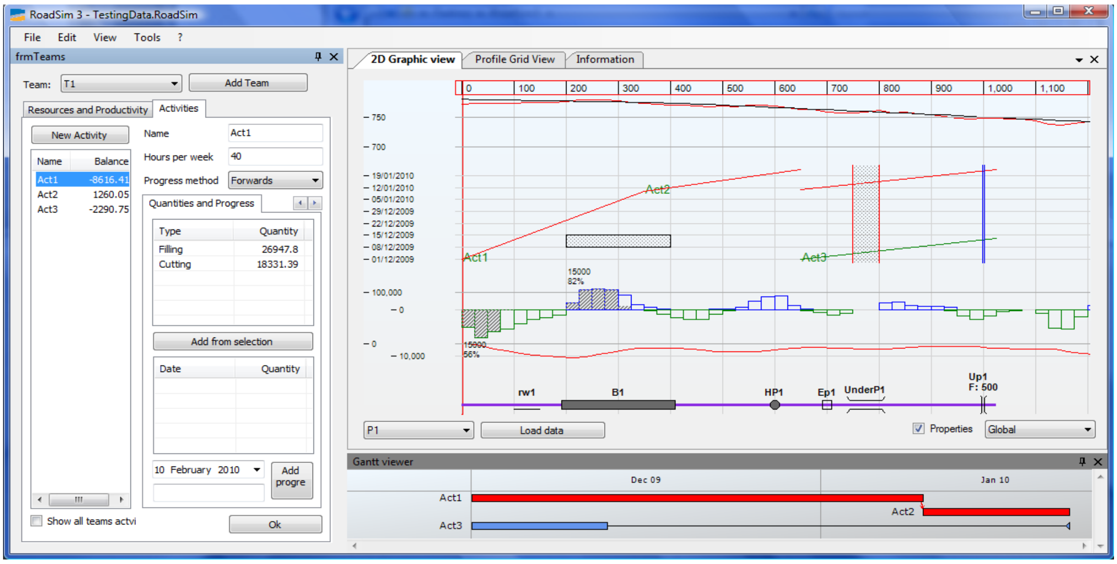


Fig. 11: Outputs of the proposed system

2.4 End-user workflow

The end user workflow is described in Figure 7. The user starts by creating and loading earthwork profiles. Based on the loaded earthwork profiles, the system will visualise earthwork volume quantities and generate Bruckner-curve (Mass-curve). The user then configures and allocates resources by creating a team that represents an atomic model which considers resource parameters and site working conditions, equipment efficiency and external factors for earthwork operations. The user can select alternative atomic models to calculate earthwork volume for the selected chainage distance area. Users can interactively select earthwork volume profiles on 2D viewer. The system then visualises the time-distance view to demonstrate working location against time duration which can be visualised in forward and backward modes. The Gantt viewer calculates the activity duration based on the selected productivity rates and selected atomic model. By selecting different atomic models or different resources, the system automatically updates the results. Together the flexibility in selecting atomic models, the simulation of resource productivity and the embedded planning capabilities help planners to continuously improve their plans by deploying the resources and sequence that enable them to meet the project end date or decrease the project duration.

The proposed approach and system are currently being verified with a number of experts and tested in a 5.6 km road project to verify the impact of the system on quality of planning and productivity of road construction sites. A report of the verification methods and results will be issued by the authors in future publications.

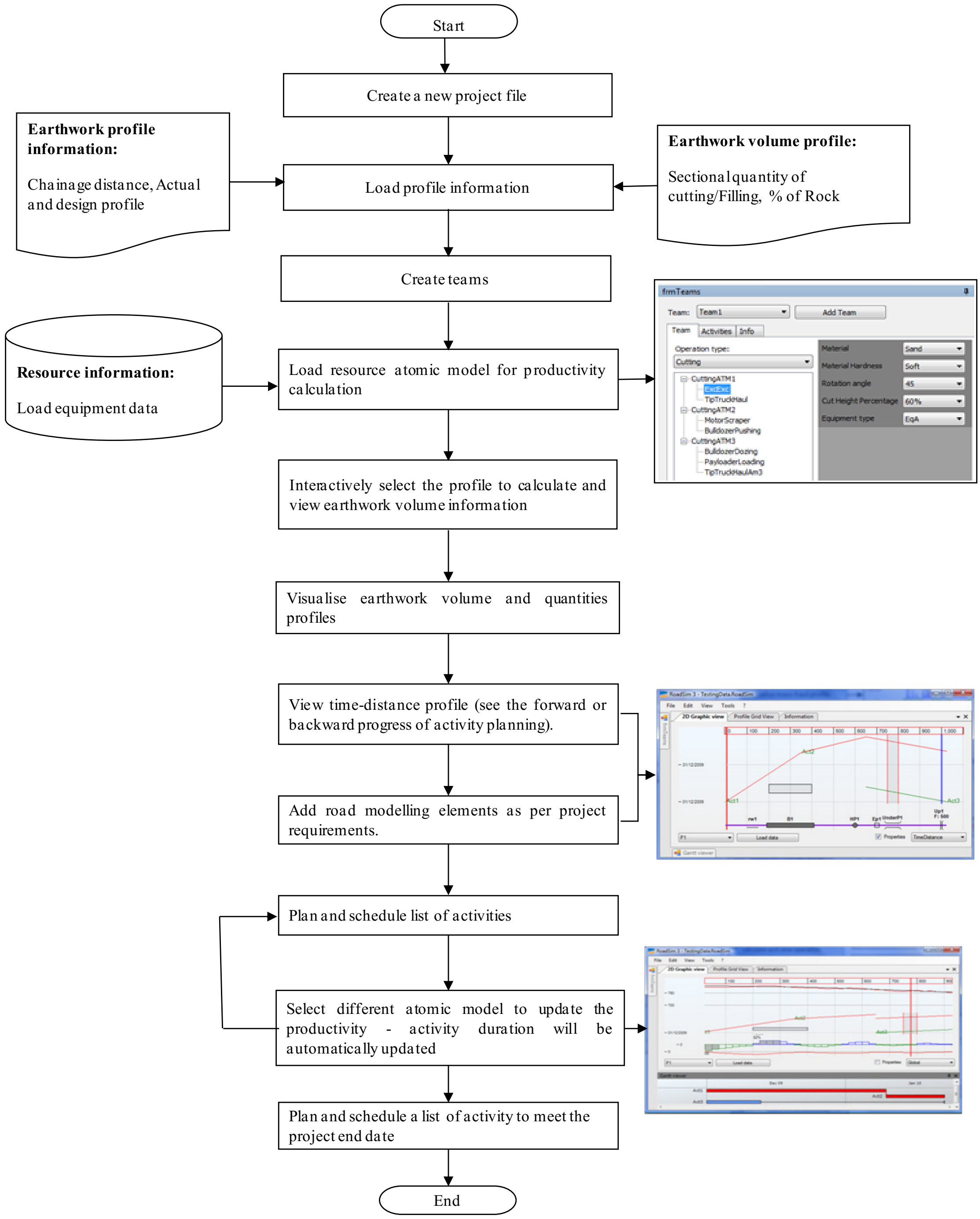


Fig. 7: End user workflows

3. CONCLUSIONS

The challenges affecting the planning of road construction projects are caused on the one hand caused by their complexity and uncertainty affected by a range of unpredictable factors (e.g. weather and site related) and on the other hand by the lack of IT systems that enable project planners to compare different strategies for resource allocation and develop more reliable plans. This paper, built upon prior work by Castro and Dawood (2005) who developed a knowledge-driven approach to reliably predict the productivity of resources, provided an interactive visual and integrated approach and tool that allow project planners addressing the complexity of earthwork operations and testing multiple what-if strategies. The integration entailed a resource information module (atomic model, resource productivity calculation, team allocation), the optimal distance calculation, the project planning and earthwork visualisation components (actual and design graph, chainage distance, mass-haul and time-distance view, Bruckner curve, road obstruction). The user interface with all these modules is interactive and planners can make changes to the resource module and schedule and immediately analyse the effect of the changes. The hypothesis made was that such an integration and interactivity would lead to reliable plans and consequently increase the productivity at the operational stage. The impact of the proposed approach and tool on the accuracy of planning of earthwork operation is being investigated with a number of road construction planning experts and in a 5.7 km road projects and results will be published in the near future.

4. REFERENCES

Askew, W.H., Al-Jibouri, S.H., Mawdesley, M.J. and Patterson, D.E. (2002). Planning linear construction projects: automated method for the generation of earthwork activities, *Automation in Construction*, Vol. 11, 643-653.

Castro, S. and Dawood, N. (2005). Roadsim: Simulation modelling applied to road construction, *International conference on Computing in Civil Engineering*, Cancun, Mexico.

Chi Ming, T., Thomas, K. L. and Bill, W. L. (2007). An integrated system for earthmoving planning, *construction management and economics*, Vol. 25 (11), 1127-1137.

Dawood, N. and Castro, S. (2009) . Automating road construction planning with a specific-domain simulation system, *Journal of Information Technology in Construction*, Vol. 14, 556-573.

Jayawardane, A. and Price A. (1994). A new approach for optimising earthmoving operations, *Proceedings of Institute of Civil Engineering*, *Transport Journal*, 105, Nov. 1994.

Kang, L.S., Jee, S.B., Kim, C.H., Pak, S.Y., and Moon, H.S. (2006). 4D System for visualisation Scheduling Progress of Horizontal Construction Project Including Earth Work, *Proceedings of the CONVR Conference 2006*, 4-6 August, Florida, USA.

Kemppainen, J., Mäkinen, J., Seppänen, O. and Kankainen, J. (2004). *Lean Construction Principles in Infrastructure Construction*, Available at: http://www.iglc2004.dk/_root/media/13058_039-kemppainen-makinen-seppanen-kankainen-final.pdf, [last accessed July 2013]

Kenley, R. (2004). Project micromanagement: practical site planning and management of work flow, *Proceedings of the 12th International Conference of Lean Construction* (IGC12), Helsingor, Denmark, pp 194-205.

Kenley, R. and Seppanen, O. (2009). Location based management of construction projects: part of a new typology for project scheduling methodologies, *Proceedings of the 2009 Winter Simulation Conference*, Austin, TX, 13–16 December, pp. 2563–70.

Liapi, A. K. (2003). 4D Visualisation of Highway Construction Projects, Proceedings of the 7th *International Conference on Information Visualisation (IV'03)*, 1093-9547/03.

Shah, R.K. and Dawood, N.N. (2011). An innovative approach for generation of a time location plan in road construction projects, *Construction Management and Economics*, Vol. 29, issue 5.

Warren, D. R. (1996). *Civil engineering construction: design and management*, Macmillan Press Ltd: London.

PART VII: NUMERICAL ANALYSIS AND OPTIMIZATION

BUILT INFRASTRUCTURE POINT CLOUD DATA CLEANING: AN OVERVIEW OF GAP FILLING ALGORITHMS

Abbas Rashidi
Georgia Institute of Technology, USA

Ioannis Brilakis
University of Cambridge, UK

Patricio Vela
Georgia Institute of Technology, USA

ABSTRACT: *Video captured from infrastructure scenes can be used to generate point cloud data (PCD) as a potential solution for acquiring spatial information of built infrastructure; however, video based PCD is incomplete and includes gaps, outliers and poor/non-reconstructed areas. This phenomenon has a negative impact on both visualization and measurement practices and is mainly caused by a number of reasons including insufficient coverage of all views while videotaping the scene, lack of sufficient features on uniform surfaces and possible errors in calibration, matching and optimization algorithms.*

To tackle this issue, researchers suggested various post processing algorithms for reconstructing missing surfaces and filling gaps/holes. This paper provides an overview on these algorithms summarize their properties in terms of efficiency, ability to work in complex geometry settings and running time. As the comparison study, three most common hole filling algorithms: MSL, GG and RFR were implemented and tested on a number of real built infrastructure scenes as the case studies. Number of generated 3D points for filling the gaps, proper distribution of points on covered surfaces and running time are three major comparison metrics has been taken into account. Results indicate that in general PML outperforms other algorithms on both flat and curved surfaces.

KEYWORDS: *Built infrastructure, triangulation, gap, Point Cloud Data, surface reconstruction.*

1. INTRODUCTION

Spatial sensing of built environments is an active field of practice and research in civil engineering with a wide range of applications including: 3D as built documentation of civil infrastructure, progress monitoring of construction projects, effective design of job site layout, structural damage assessment and quality control of construction products. Results of spatial sensing of built infrastructure are ultimately presented in the form of point cloud data (PCD) (Brilakis et al., 2011)). Two major approaches are utilized for reconstructing built environments and generating PCD: using active sensors (e.g. laser scanners) and using passive sensors (e.g. digital camera). It is well known that using laser scanners results in generating denser PCD with higher qualities however, neither of the approaches is able to generate nearly perfect PCD. Some areas might be poorly reconstructed and there are always gaps or holes on the surfaces of PCD. This phenomenon usually happens due to a number of reasons including accessibility issues and occlusions (for laser scanners) and insufficient coverage of the scene, occlusions, lack of sufficient number of textures on the surfaces of elements and possible errors in calibration and optimization algorithms (for image/video based techniques).

One possible solution to this issue would be generating the PCD, identifying the missing/poorly reconstructed areas and trying to re-scan the scene to acquire extra 3D points. This solution is not always feasible since there might be changes in the original scene over the time. In addition, re-scanning the scene is not helpful if gaps/hole occurred due to reasons such as lack of texture or computational errors. As the result, adding a post processing step for cleaning generated PCD and filling gaps/holes is crucial.

For most applications, gaps on surfaces of PCD are not appropriate. Depending on the size/location, gaps may cause two problems: They negatively impact the quality of PCD when it comes to visual representations. PCD

Citation: Rashidi, A., Brilakis, I. & Vela, P. (2013). Built infrastructure point cloud data cleaning: an overview of gap filling algorithms. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

entail several gaps and poorly reconstructed areas are not eye catching. The second problem is related to proper extraction of geometric information from PCD. Gaps, holes and incomplete areas might be located on edges and intersections of elements and those locations are extremely significant for conducting length measurements and extracting geometric information of the scene (Figure 1).

Fig. 1: It is not possible to extract the geometric information of poorly reconstructed areas.

To tackle the issue, a number of algorithms are proposed for filling the gaps on smooth surfaces. This paper provides an overview of existing algorithms, as well as advantages and shortcoming of these methods for real applications in the area of civil infrastructure. To these end, three of the most popular algorithms are implemented and tested on different real cases of civil infrastructure. The rest of the paper is organized as follows:

A brief overview of current algorithms for filling the gaps, as well as major characteristics of each algorithm is presented in section 2. Sections 3 and 4 briefly summarize our approach for implementing the three most common algorithms for filling the holes and explain the procedure for conducting experiments on real built infrastructure datasets to evaluate the performance of the above mentioned algorithms. Results of the comparison study are summarized in section 5, and finally conclusions and plans for future research are presented in section 6.

2. FILLING THE GAPS ON SURFACES OF POINT CLOUD DATA

The process of hole-filling on PCD can be divided into two steps: 1) determining locations of gaps/holes and 2) smoothly covering the hole and reconstructing missing parts using available data (Wang and Oliveira (2002)). For several applications, holes/gaps on surfaces of built infrastructure PCD present simple topology, i.e. the holes are located on flat surfaces. The situation is more challenging when holes are located on intersection of different surfaces, or geometrically complex surfaces. Existing algorithms for filling holes/gaps are classified into three major categories:

i) Algebraic methods which reconstruct the missing surfaces by fitting appropriate functions based on sets of neighbor points as the input. This approach works very well for holes with simple structure located on flat/curved surfaces but is not able to successfully cover the holes located on more geometry complex or twisted surfaces.

ii) Computational geometry: Under this class of algorithms, different computational approaches such as region growing and Delaunay triangulation and usually leave under sampled areas.

iii) Implicit functions: this group of algorithms uses various implicit functions for reconstructing missing parts and covering holes. This category is the most popular approach for filling gaps/holes however; these groups of algorithms are not able to reconstruct the missing parts in the case that surfaces have boundaries.

General properties of different algorithms suggested by researchers are presented in table 1:

Table 1: An overview of existing algorithms for filling gaps/holes on PCD

Category	algorithm	Reference	Input data	Holes with boundaries?	Geometric complex surfaces?
Computational geometry	Voronoi-Based surface reconstruction	Amenta et al. (1998)	meshes	yes	no
	Delaunay triangulation	Edelsbrunner and Muche (1994)	points	no	no
	Projection-based approach for region growing	Gopi and Krishnan(2000)	meshes	yes	no
	Graph-based approach for region growing	Mencl (1995)	meshes	yes	no
	Ball Pivoting Approach	Bernardini et al. (1999)	points	yes	yes
Algebraic methods	Generalized implicit functions approach	Scarloff and Pentland (1991)	meshes	yes	no
	Dynamic implicit functions approach	Terzopoulos and Metaxas (1991)	points	yes	no
Implicit methods	Volumetric Diffusion	Davis et al. (2002)	Partial meshes	yes	yes
	Moving Least Square Method	Wang and Oliveira (2007)	Points and meshes	yes	no
	Compactly supported radial basis functions	Morse et al. (2001)	points	yes	yes

To evaluate the performance of gap filling algorithms, we focus on three most popular methods vastly used in computer graphic domain:

2.1 Moving Least Square Method (Suggested by Wang and Oliveira (2007))

A brief description of Moving Least Square method is presented in this section (Wang and Oliveira (2007)):

In order to fill holes, extra 3D points should be added to the un-sampled regions. For this end, the algorithm first identifies hole's boundaries and their vicinities. For each hole, the algorithm fits a plane through the vicinity points and, for each corresponding point, calculates the distance of the new point to this plane as well as its projection onto the plane. This set of distances forms a height field around the hole which is then applied for surface fitting. Following this procedure, the problem of reconstructing holes in 3D is converted to a simpler interpolation problem. Once a surface has been fitted to the height field using MLS, new points for filling the hole can be obtained by re-sampling the fitted surface. The basic version of the algorithm is presented as the following step-by-step algorithm:

1. Generate the triangle mesh from the input point cloud;

2. Repeat

   3. Automatically identify a whole boundary and its vicinity;

   4. Compute a reference plane for the hole vicinity;

   5. Calculate the distances between the vicinity points and the above mentioned plane;

   6. Fit a surface through this height field using MLS;

7. Cover the hole by re-sampling the fitted surface;

8. until no holes exist.

2.2 The Ball-Pivoting Algorithm (Suggested by Bernardini et al. (1999))

The Ball-Paving Algorithm is based on a pretty simple principle. Assume that the manifold M is the three dimensional surface of an element of the scene and S is a point sampling of M. If we consider S dense enough, we can assume that a ball with ρ radius is not able to pass through the surface without touching sample points. We can also place the ρ-ball in contact with three sample points. That being said, we can keep the ball in contact with two sample points and pivot the ball until it touches the third point. We can pivot around each edge of the hole boundary so the ball contacts form new triangles. The set of triangles which are formed while the ball is traversing on the hole's area continuously cover the surface of the hole. The procedure is also depicted in figure 2 where the pivoting ball touches three vertices of the triangle $\tau = (\sigma_i, \sigma_j, \sigma_0)$whose normal is n. The z axis is perpendicular to the page surface and points towards the viewer and m is the origin of the coordinate system. The circle $s_{ij0}$is located at the intersection of the ρ-ball with z=0. During the pivoting procedure, the ρ-ball touches two edges with endpointsσ_i, σ_j and the ball center represents a circular trajectory γ whose center is m and the radius$\|c_{ij0} - m\|$. During the pivoting stage, the ball hits a new data point,σ_k. If we considerss_k as the intersection of aρ-sphere centered at σ_k with z=0. The centerc_k of the pivoting ball when it hits σ_k is the intersection of γ with s_k located on the negative half-plane of oriented line l_k. More details can be found at Bernardini et al. (1999).

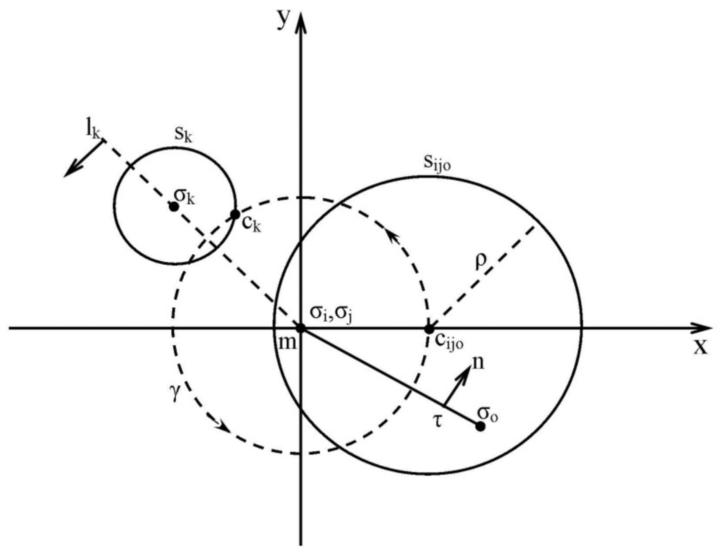


Fig. 2: Pivot Ball Algorithm

2.3 Volumetric Diffusion Method (Suggested by Davis et al. (2002))

As the first step of this method, the surface is first converted into a volumetric representation which is a spaced 3D grid of values of a clamed sign distance function represented as ds(x) (Davis et al. (2002)). This function is merely defined in a narrow band near the observed surface, and it is positive inside the surface and negative outside. Since the units of the function are not important, it is defined to be in the range from -1 to 1 over the width of the band. The thickness of the band does not have a significant impact on the result; so based on the authors' recommendation, 5voxels on either side of the observed surface were considered. As suggested by the authors, the VRIP algorithm was implemented to build this function directly from the PCD. At the same time an associated weight function w(s) was defined, which ranges from 0 to 1 and measures the confidence in the values of ds. In most areas w(s) = 1, but it typically decreases near boundaries of the observed surface, where noise increases.

The goal of the volumetric diffusion algorithm is to extend ds to a function that is defined over the entire volume, though in practice it is only required to compute d near the surface (in fact only near holes in the surface). This can be done by diffusing the values of ds outward from the observed surface into adjoining undefined areas. In particular, the diffused function propagates inward across the holes, eventually spanning them. Once diffusion is complete, the zero set of this function is the desired hole-free surface. More information about the diffusion method can be found at (Davis et al. (2002)).

3. COMPARISON MATRICS

Built infrastructure elements possess some unique characteristics, which should be taken into account when it comes to evaluating the performance of algorithms for filling/covering the gaps. In many cases, infrastructure scenes consist of elements with flat surfaces, e.g. surface of brick walls, rectangular concrete columns, plywood sheets and gypsum panels. However, curved surfaces also might be found among other types of built infrastructure elements. Circular concrete columns and arches are examples of these curved surfaces. The focus of this paper is on simple flat surfaces and gaps/holes with more complex geometry, e.g. those located on curved surfaces or intersection of several elements, are not within the current scope of our work. It is necessary to mention that by flat surfaces, we mean regular flat surfaces found in built environments such as surfaces of concrete and masonry walls; despite the fact that some of these elements are not mathematically defined as perfect planar surfaces and there might be small curves involved.

To evaluate the performance of the algorithms, two major criteria were considered: 1) running time of the algorithm and 2) their capabilities in finding gaps and properly covering them. The second property is quantitatively measured by using two matrices: number of generated 3D points for filling gaps and uniformity in distribution of the generated 3D points on the covered surfaces of holes. To evaluate the uniform distribution of added 3D points for covering the hole's surfaces, the following approach has been implemented: First the surface of different elements of built infrastructure case studies are partitioned into small square regions (2×2cm in this study). The surface is considered as successfully reconstructed if for each square, there is a corresponding 3D in the improved PCD after filling gaps. The percentage of coverage or completeness is then calculated as the ratio of the number of successfully reconstructed squares over total number of squares.

4. COMPARISON RESULTS

To evaluate the performance of the three major algorithms for filling holes/gaps, a C# based prototype was implemented. It was written in Visual Studio 2010 using Windows Presentation Foundation (WPF) and publicly available libraries such as Open CV 2.0 (wrapped by EmguCV) for access to computer vision tools and DirectX 10 for the graphic display of results (Dai et al., (2013)). To conduct the experiments, we selected five built infrastructure scenes with flat surfaces as our case studies. The selected case studies include concrete stairs (case#1), a masonry wall (case#2), a brick wall (case#3), a rectangular concrete column (case#4) and a plywood panel (case #5). Each scene was videotaped from multiple viewpoints to minimize occlusions. An off-the-shelf Canon Vix-731 ia HF S100 was utilized for data collection purposes. The captured video clips were processed and the PCD for each built infrastructure scene was generated following the procedures explained in Rashidi et al. (2013). Three major hole filling algorithms are then implemented on the generated PCD to cover the existing gaps. Percentages of completeness and number of points before and after implementing the algorithms as well as running time for each algorithm are measured. Snapshots of the generated point clouds before and after using algorithms are depicted in figures 4 and 5:

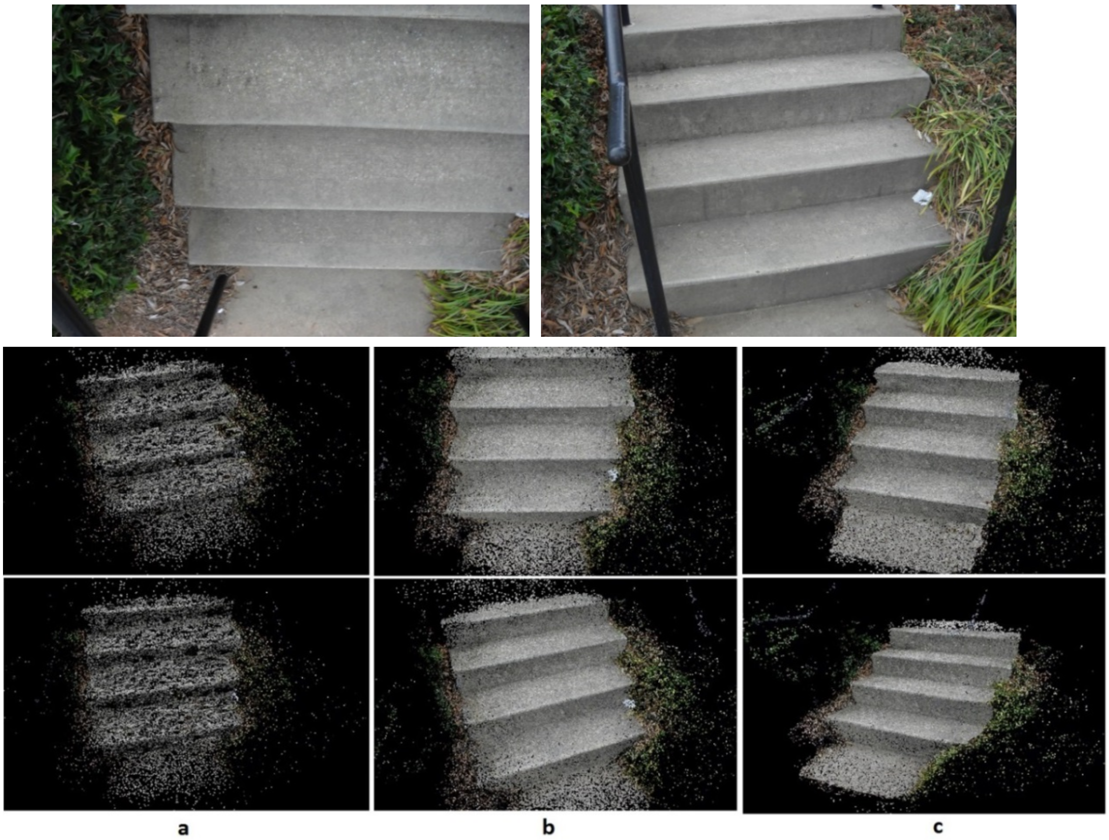


Fig. 4: sample snapshots of results of implementing algorithms on the concrete stairs dataset: a) generated PCD b) results of using VDM c) results of using MLS method

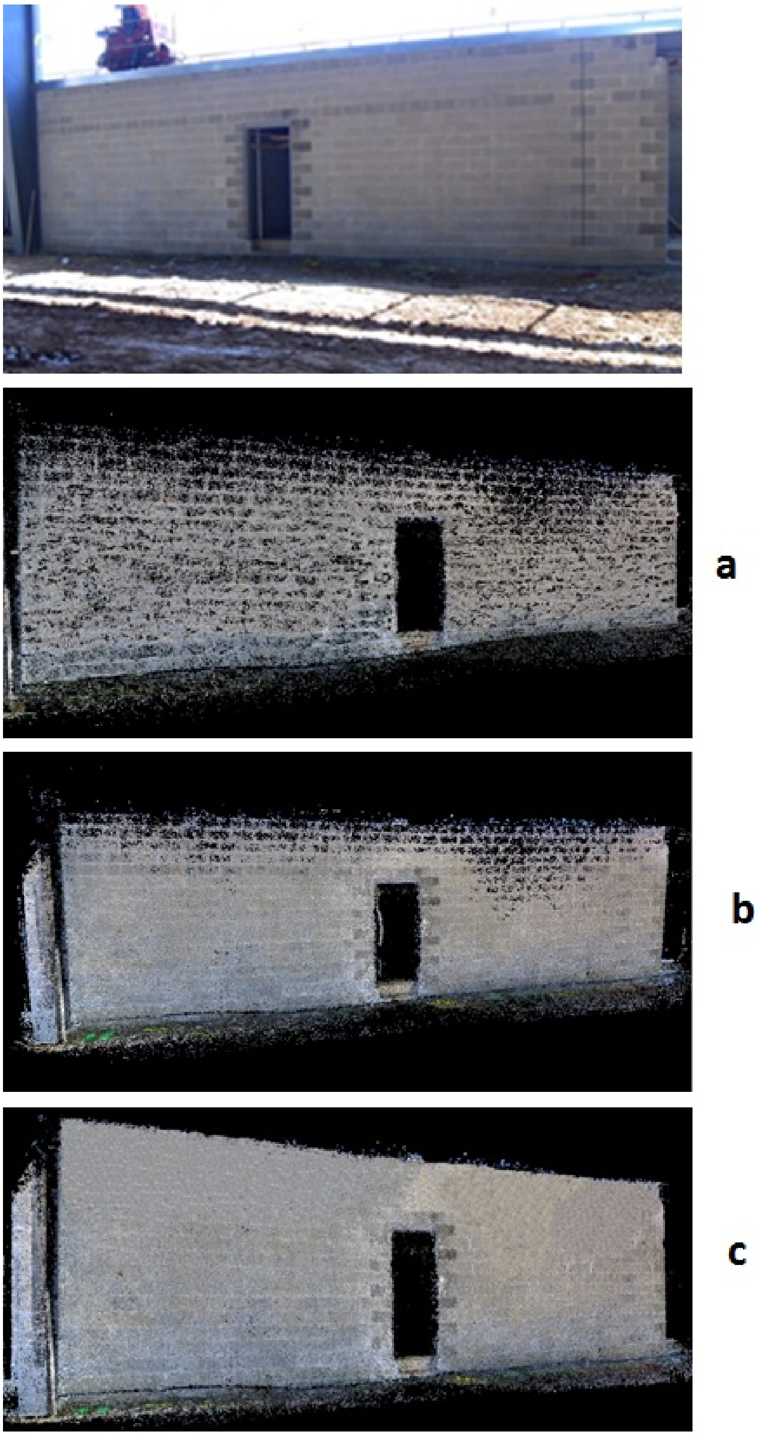


Fig. 5: Sample snapshots of results of implementing algorithms on the concrete stairs dataset: a) generated PCD b) results of using BPA c) results of using MLS method.

The summery of the comparison results are presented in table 2. As shown in the table, MLS outperforms other algorithms in terms of successfully filling the gaps; however, compared to the other two algorithms the processing is slower.

.Table 2: Summary of comparison results for 5 different datasets.

Dataset #	Method	Number of points before implementing the algorithm	Number of points after implementing the algorithm	Completeness before implementing the algorithm (%)	Completeness after implementing the algorithm (%)	Run time (second)
1	MLS*	459’412	512’307	82.74	95.15	39
	VDM**	459’412	483’251	82.74	91.32	37
	BPA***	459’412	491’775	82.74	89.43	21
2	MLS	2’578’209	2’876’292	79.21	88.10	51
	VDM	2’578’209	2’793’251	79.21	84.49	47
	BPA	2’578’209	2’655’439	79.21	81.98	37
3	MLS	782’891	841’257	73.65	86.21	35
	VDM	782’891	804’219	73.65	84.54	33
	BPA	782’891	812’593	73.65	80.22	28
4	MLS	1’021’544	1’261’004	85.74	93.24	42
	VDM	1’021’544	1’110’736	85.74	92.73	38
	BPA	1’021’544	1’008’703	85.74	88.41	33
5	MLS	678’325	697’841	86.29	94.91	36
	VDM	678’325	692’610	86.29	91.65	32
	BPA	678’325	683’541	86.29	92.81	26

*MLS: Moving Least Square method

** VDM: Volumetric Diffusion Method

*** BPA: Ball-Pivoting Algorithm

5. SUMMARY AND CONCLUSION

PCD data generated by processing video/images are usually imperfect and there are holes/gaps poorly reconstructed areas. Multiple reasons such as insufficient coverage of images/video frames, texture-less surfaces and possible errors in 3D reconstruction algorithms might cause this issue. Holes/gaps on surfaces negatively affect the visual quality of PCD. In addition, poorly constructed areas might cause problems while extracting geometric information/length measurements from PCD. As the result, post processing algorithms for fixing the problem and covering holes and gaps are required.

This paper presented an overview of existing algorithms for filling gaps on smooth surfaces of built infrastructure. The performance of three major algorithms in this field; i.e., Moving Least Square, Volumetric Diffusion Method and Ball-Pivoting Algorithm were quantitatively evaluated using five built infrastructure scenes as case studies. The scope of current paper was flat surfaces. The results showed that overall Moving Least Square method outperforms the other two algorithms in terms of quality of the generated covers for filling gaps and reconstructing missing parts. As the next phase of the research, the authors intend to evaluate the performance of the algorithms on more challenging cases, e.g. curved surfaces and geometrical complex holes.

6. REFERENCES

Amenta N., Bern M. and Kamvysselis M. (1998).A new voronoi-based surface reconstruction algorithm, *Proceedings of the SIGGRAPH'98*, 415-421.

Brilakis I., Fathi H. and Rashidi A. (2011). Progressive 3D Reconstruction of Infrastructure with Videogrammetry, *Journal of Automation in Construction*, Vol. 20, No. 7, 884-895.

Bernardini F., Mittleman J., Rushmeier H., Silva C. and Taubin, G. (1999). The Ball-Pivoting Algorithm for surface reconstruction, *IEEE Transactions on Visualization and Computer Graphics*, Vol. 5, No.4, 349-359.

Dai F., Rashidi A., Brilakis I. and Vela P. (2013).Comparison of Image- and Time-of-Flight-Based Technologies for 3D Reconstruction of Infrastructure,*ASCE Journal of Construction Engineering and Management*, Vol. 139, No. 1, 69-79.

Davis J., Marschner S., Garr M. and Levoy M. (2002).Filling holes in complex surfaces using volumetric diffusion, *Proceedings of the First international Symposium on 3D Data Processing*, *Visualization, Transmission*, 428-438.

Edelsbrunner H. andMuche E.P. (1994). Three-dimensional alpha shapes, *ACM Transactions on Graphics*, Vol. 13, No. 1, 43-72.

Gopi M. and Krishnan S. (2000). A fast and efficient projection based approach for surface reconstruction, *International Journal of High Performance Computer Graphics*, *Multimedia and Visualization*, Vol. 1, No. 1, 1-12.

Mencl R. (1995).A graph-based approach to surface reconstruction, *Proceedings of EUROGRAPHICS'95*, *Computer Graphics Forum*, Vol. 14,No. 3, 445-456.

Morse B. S., Yoo T. S., Chen D. T., Rheingans P. and Subramanian K. R. (2001). Interpolating implicit surfaces from scattered surface data using compactly supported radial basis functions,*Proceedings of the International Conference on Shape Modeling & Applications*, IEEE Computer Society Press, 89-98.

Rashidi A., Dai F., Brilakis I. and Vela P. (2013).Optimized Selection of Key Frames for Monocular Videogrammetric Surveying of Civil Infrastructure,*Journal of Advanced Engineering Informatics*,Vol.27, No.2, 270-282.

Scarloff S. andPentland A. (1991).Generalized implicit functions for computer graphics, P*roceedings of the SIGGRAPH'91*, 247-250.

Terzopoulos D. and Metaxas D. (1991). Dynamic 3D models with local and global deformations: deformable superquadrics, *IEEE Transactions on Pattern Analysis and Machine Intelligence*, Vol. 13, No. 7, 703-714.

Wang J. and Oliveira, M. M. (2002). Improved scene reconstruction from range images, *Proceedings of the EUROGRAPHICS'02*, 521-530.

Wang J. and Oliveira M.M. (2007).Filling holes on locally smooth surfaces reconstructed from point clouds, *Image and Vision Computing*, Vol. 25, No. 1, 103-113.

3D SCAN PLANNING OF OUTDOOR CONSTRUCTIONS BASED ON PHOTOGRAMMETRIC MODEL AND MATHEMATICAL OPTIMIZATION

Hiroshige Dan, Yoshihiro Yasumuro, Taisuke Ishigaki & Tatsuaki Nishigata
Kansai University, Japan

Masataka Imura
Osaka University, Japan

ABSTRACT: *A 3D scanner is capable of capturing surface shapes of the objects as a set of "point cloud" and is extending its applicability toward examining, re-designing and preserving the existing constructions as well as on-site information for BIM. One of the most difficult problems to collect complete surface data of outdoor constructions is to avoid self and mutual occlusions. If we want to collect complete data for covering whole surfaces of the constructions, then we have to measure them from multiple points usually. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. So it is very important to make an effective measurement plan a priori for avoiding redundancy for both labor and computational costs. In this research, therefore, we propose a method for 3D-scan planning of outdoor constructions based on photogrammetric models and mathematical optimization methods. In our proposed method, we first use photogrammetric techniques and make a rough 3D model of measurement scenery: we take photographs of the targets by a calibrated digital camera, and find corresponding characteristic points over the photographs, for example corners and intersection points of edge lines. Next, we triangulate the corresponding points by using 3D photo-modeling software. Finally, we obtain the rough 3D mesh model. After that, we make the optimal scan plan based on the rough 3D mesh model by using some mathematical methods: we examine the visibility and self/mutual occlusion property of each polygon of the 3D mesh, and calculate the minimum number of measurement points and their layout to scan all the surfaces of the targets. Moreover, our proposed method can calculate the optimal layout of the designated number of measurement points to maximize the obtainable data.*

KEYWORDS: *3D-Scan Planning, Photogrammetric Model, Mathematical Optimization.*

1. INTRODUCTION

A laser range scanner is a 3D surface imaging system which can obtain the surface data of target objects by performing a number of independent ranging, and a 3D image emerges by merging them. Laser scanners can be used for consistent and vast assessment of spatial conditions required by a variety kinds of construction applications such as investigation of management of construction processes (Shih et al. 2004, 2006), monitoring the as-built infrastructures (Miller et al. 2008), consequences of disasters (Watson et al. 2011) and so forth. Most of these applications require timely spatial information delivery. Collecting the needed information within limited time, therefore, is critical for many field applications on construction sites.

One of the most difficult problems to collect the complete surface data of target objects is to avoid occlusions. For collecting the complete data, we have to measure the objects from multiple viewpoints usually. However, examining multiple surface visibilities relative to variable multiple viewpoints is a complicated problem. Moreover, multiple measurements require plenty of time and labor, and each measurement gives a data set consisting of hundreds of millions of 3D points to be processed for further computations. Hence, it is very important to make an effective measurement plan a priori for avoiding redundancy for both labor and computational costs.

Since the advent of laser scanners, designing efficient and effective operation methods of a laser scanner has been developed as view planning. The existing view planning techniques are trial-based schemes, which segment

Citation: Dan, H., Yasumuro, Y., Imura, M., Ishigaki, T. & Nishigata, T. (2013). 3D scan planning of outdoor constructions based on photogrammetric model and mathematical optimization. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

scanned and unscanned regions in the target area to find the next best scanning viewpoint for minimizing the unscanned regions. This approach includes the methods for improving efficiency of sequential scanning (Asai et al. 2007, Pitto 1999, Pulli 1999) and three-dimensional environmental map generation by autonomous mobile robots (Blaer and Allen 2009, Grabowski et al. 2003, Surmann et al. 2003). These view planning techniques are designed for coping with a dilemma; the geometrical topology of the object is unknown until it is scanned. And thus the sequential scheme to estimate the next best viewpoint is based on the scanned data configuration. In other words, sequentially searching approaches do not meet the demands for outdoor scanning, where estimating the minimum time and cost for the whole scanning task before starting the survey process is important for practical operation.

For this problem, the authors proposed a method for making a measurement plan by using a ground plan of a target area as prior information (Dan et al. 2010). This method generates an optimized initial view plan prior to the on-site survey by using mathematical optimization. However, this method is based on a 2D plan, and hence, it is useful only for the cases where the height differences of the objects are not important comparatively. Therefore, in this paper, we propose an effective planning method for 3D geometry of the jobsite by calculating visibility and the amount of obtainable data based on simple photogrammetry techniques for preliminary survey. Since the view planning method itself follows the mathematical optimization framework, finding the least number of measurements needed to measure all the surfaces of the objects and the viewpoints' setup to maximize the total amount of scanned data within the limitation of the number of measurements.

2. GOAL AND APPROACH

The goal of this research is to propose a method for making a plan to scan the target outdoor constructions by using a 3D scanner. The scan plan must specify the scanning points from which we can scan all the surfaces of the target constructions.

To make a scan plan, we have to estimate the visibility of the faces of the target objects and the quality of the scan data. When we use a 3D scanner, it is the most important to consider the visibility of the target objects from the points we set a 3D scanner, and the visibility is determined by self and mutual occlusion. Self occlusion occurs when a part of the target object overlaps itself while seeing from a viewpoint. On the other hand, mutual occlusion occurs when the other target overlaps the target object. Self and mutual occlusion interferes scanning, and hence we must examine the occlusion property in the target area. Also, quality of the scan data highly depends on the scan density since the 3D shape information can be only read from the point set of the scan data. Higher and uniform scan density is preferable in general.

It is necessary for estimating the visibility and the scan quality to model the onsite condition, that is, the object and surroundings geometries. In this research, we employ photogrammetric techniques to model the target area. Also, we triangulate the obtained model. Triangulation of the surfaces of 3D objects is very common, and it is very advantageous to estimate the visibility and the scan density.

A scan plan should have good properties to meet the following requests:

[Request 1] We can scan all the surfaces of targets with avoiding self and mutual occlusion.

[Request 2] The number of times we scan should be minimized.

[Request 3] The amount of the obtainable data should be maximized with the limited number of scans.

To find the scan plan which has these properties, we employ mathematical optimization. First, we formulate and solve the optimization problem for [Request 1] and [Request 2]. The solution of this problem gives us the number of scans to respond to [Request 1] and [Request 2]. After that, we formulate another optimization problem for [Request 3] and this problem is solved with the minimum number of scans which is obtained from the previous problem. Moreover, the values of parameters used for formulating these problems can be determined from the photogrammetric model which we explained above.

In Section 3, we explain the photogrammetric modeling of the target area and its triangulation. In Section 4, we explain a method for examining the visibility and the scan density by using the photogrammetric model. And in Section 5, we consider the optimization models to find the optimal view plan.

3. PHOTOGRAMMETRIC MODELING FOR CONFIGURATION SETUP

In this research, photogrammetric models play a role to allow simulating the visibility of the target objects from candidate viewpoints of the scanner. To represent the 3D region occupied by the objects, its 3D model is prepared as a polygon model circumscribing the object volume. The 3D model of the objects consists of polygon meshes whose faces can be used for checking not only their visibilities but also their scan density from the viewpoints. The 3D model of the surrounding structures produces possible visual occlusion from a certain viewpoint to the surfaces of the objects.

To prepare this 3D model, photo-based modeling is suitable for scanning plan of many construction applications, since taking photos is common procedure for preliminary survey of the jobsite. In recent years, several stereo-vision types of digital cameras are available and make it easy to collect multiple-view photos. Furthermore, web-based application providing onsite photos from pedestrian’s point of view and aerial photos taken from multiple viewing angles are open to the public and can be used for the planning even at office nowadays. For example, Google Street-view and Google Earth provide us such photos.

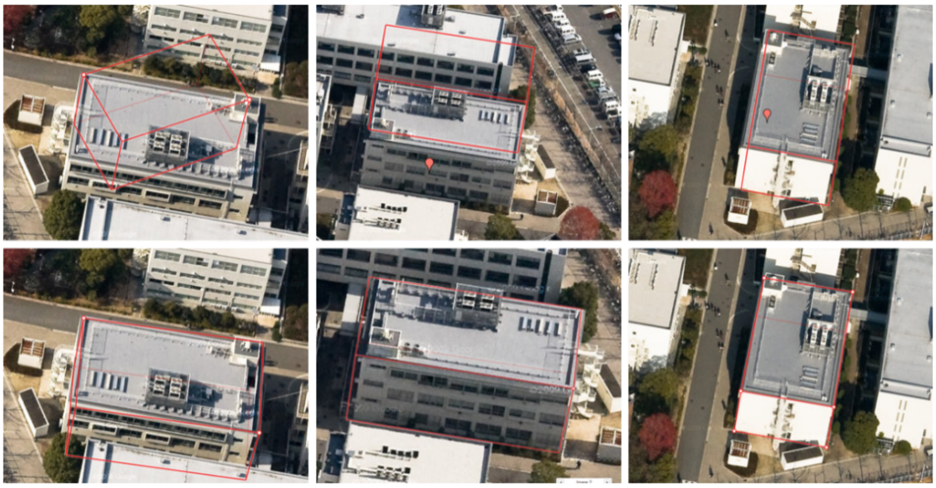


Fig. 1: Modeling process by Building Maker; Adjusting the size and positions of the bocks corners to that of building on the photos

Specifying corresponding points on the objects between multiple photos, visual triangulation can be performed to reconstruct 3D coordinate of the corresponding points e.g. corners of pillars, beams and sashes etc. of the buildings (Hartley et al. 2004). In addition, many kinds of commercial software for photogrammetry are also available, e.g. PhotoModeler, 2D3, Google SketchUp, Building Maker and so on (Figures 1, 2 and 3).

Fig. 2: Example of aerial photo set from multiple views; a building with a balloon is the target**.**

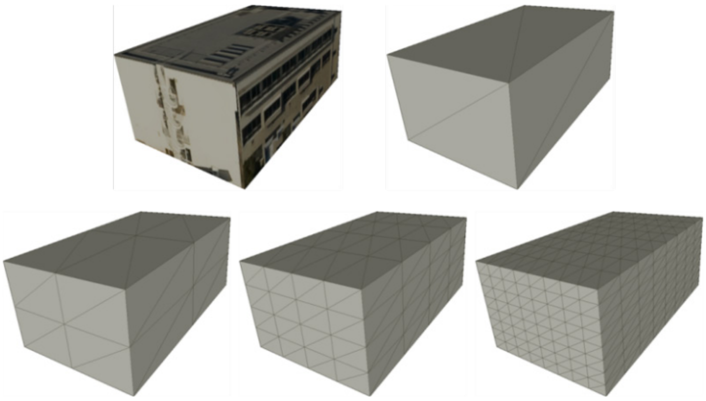


Fig. 3: Object model by Building Maker with and without texture (upper left and right), and recursively subdivided mesh models with mid-points method (lower).

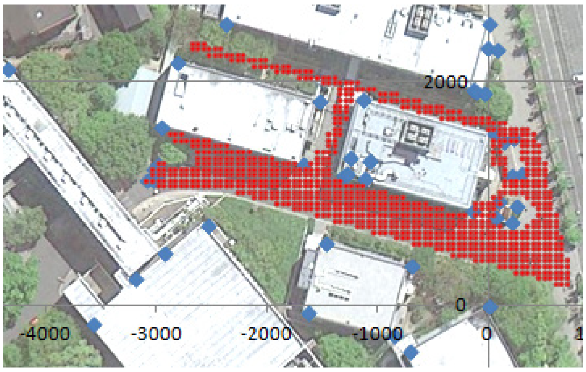


Fig. 4: Example of candidate viewpoints arrangement; Each red dot is a candidate viewpoint.

Moreover, we have to prepare candidate viewpoints, where the 3D scanner can be settled, in the obtained model (Figure 4).

4. VISIBILITY AND SOLID ANGLE OF TRIANGLE

As mentioned in the previous section, the surfaces of all the objects in the target area are approximated by triangles and a part of them are the target triangles, which have to be measured by a 3D scanner. For these triangles, we have to examine the visibility from the candidate viewpoints to make a scan plan. Moreover, the solid angles of the triangles viewing from the candidate viewpoints are also needed.

4.1 Visibility

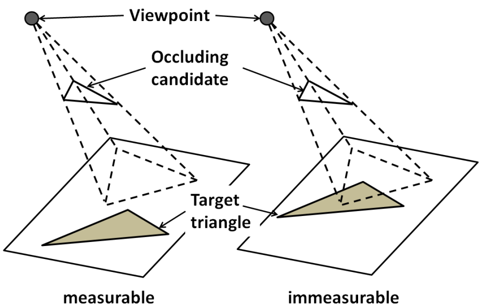


Fig. 5: Relationship between a viewpoint and a target triangle

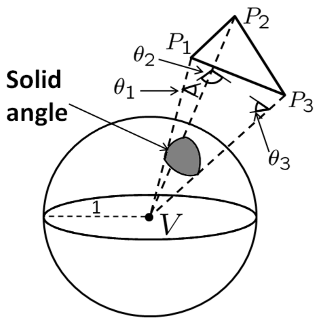


Fig. 6: Solid angle

Figure 5 shows the relationship between a viewpoint and a target triangle. If a triangular pyramid generated by a viewpoint and a target triangle intersects another occluding triangle, then the target cannot be scanned from the viewpoint; otherwise, it is measurable. To examine such relationship, we have to employ some mathematical methods. The authors have already proposed a method for this examination (Dan et al., 2011).

4.2 Solid Angle

For the case that $\Delta P_1P_2P_3$ is measurable from V, we have to calculate the amount of data which would be obtained by a 3D scanner. From the principle of a 3D scanner, the amount of obtainable data is proportionate to the solid angle of $\Delta P_1P_2P_3$ from V. A solid angle of $\Delta P_1P_2P_3$ from V is defined to be the area of the intersection of the cone generated by V and $\Delta P_1P_2P_3$ and a sphere of unit radius (Figure 6).

It is known that the solid angle of $\Delta P_1P_2P_3$ from V can be obtained by

$$s = \theta_1 + \theta_2 + \theta_3 - \pi,$$

where $\theta_i\,(i = 1,2,3)$ are the three angles between three side faces of the triangular pyramid V - $P_1P_2P_3$ (Figure 6).

5. SCAN PLANNING BY MATHEMATICAL OPTMIZATION

In this section, we formulate two 0-1 integer optimization problems. As discussed above, these models have been proposed in the previous research (Dan et al., 2010). We use the same model in this paper.

We will use the following symbols in the mathematical optimization models in this paper:

[Sets and Indexes]

- $i \in I$: candidate points for measurement,
- $t \in T$: triangles on the surfaces of measurement objects.

[Variables]

$$x_i := \begin{cases} 0, & \text{a candidate point } i \text{ is unadopted as a viewpoint,} \\ 1, & \text{a candidate point } i \text{ is adopted as a viewpoint.} \end{cases}$$

[Parameters]

$$d_{it} := \begin{cases} 0, & \text{a triangle } t \text{ is unmeasurable from a candidate point } i, \\ 1, & \text{a triangle } t \text{ is measurable from a candidate point } i, \end{cases}$$

$$a_{it} := \begin{cases} 0, & d_{it} = 0, \\ \text{the amount of scanned data on a triangle } t \text{ from a candidate point } i, & d_{it} = 1, \end{cases}$$

$r :=$ the upper bound of the number of measurement.

Note that we can calculate the values of parameters, d_{ij} and a_{ij}, from the 3D model on the target area, as we explained in the previous section.

In this paper, we use these two mathematical optimization models (Dan et al, 2010):

$$\begin{array}{ll} \text{minimize} & \sum_{i \in I} x_i \\ \text{subject to} & \sum_{i \in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\ & x_i \in \{0,1\}. \end{array} \tag{1}$$

$$
\begin{aligned}
&\text{maximize} && \sum_{i\in I, j\in J} a_{ij} x_i \\
&\text{subject to} && \sum_{i\in I} d_{ij} x_i \geq 1 \quad (\forall j \in J), \\
& && \sum_{i\in I} x_i \leq r, \\
& && x_i \in \{0,1\} \quad (\forall i \in I).
\end{aligned}
\tag{2}
$$

The objective function of (1) is to minimize the number of viewpoints. Also, the term $d_{ij}x_i$ in the first constraint of (1) means as follows:

$$
d_{ij}x_i := \begin{cases} 0, & \begin{array}{l}\text{a candidate point } i \text{ is unadopted as a viewpoint } (x_i = 0) \\ \text{or a triangle } j \text{ is unmeasurable from } i \ (d_{ij} = 0),\end{array} \\ 1, & \begin{array}{l}\text{a candidate point } i \text{ is adopted as a viewpoint } (x_i = 1) \\ \text{and a triangle } j \text{ is measurable from } i \ (d_{ij} = 1).\end{array} \end{cases}
$$

Therefore, the first constraint of (1) means that all the triangles should be measured from one viewpoint at least. Consequently, we can find the least number of viewpoints to scan all the target triangles by solving (1).

The term $a_{ij}x_i$ of the objective function of (2) means as follows:

$$
a_{ij}x_i := \begin{cases} 0, & \begin{array}{l}\text{a candidate point } i \text{ is unadopted as a viewpoint } (x_i = 0) \\ \text{or a triangle } j \text{ is unmeasurable from } i \ (a_{ij} = 0),\end{array} \\ a_{ij}, & \begin{array}{l}\text{a candidate point } i \text{ is adopted as a viewpoint } (x_i = 1) \\ \text{and a triangle } j \text{ is measurable from } i \ (a_{ij} > 0).\end{array} \end{cases}
$$

Therefore, the objective function of (2) is to maximize the sum of the amount of scanned data. In addition, the second constraint of (2) is to restrict the number of measurements less than or equal to r. Here, r is normally equal to the optimal value of the problem (1), that is, the minimum number of viewpoints to scan all the surfaces of the targets. Consequently, by solving (2), we can obtain the optimal layout of r viewpoints to collect the scanned data as much as possible.

6. EXPERIMENTS AND DISCUSSIONS

In this section, we report some practical experiments by using our proposed method and discuss about the obtained result.

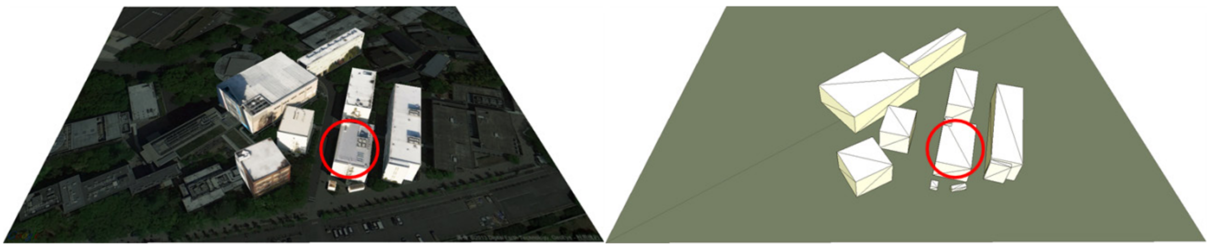


Fig. 7: The target building (left) and 3D mesh model around the target (right)

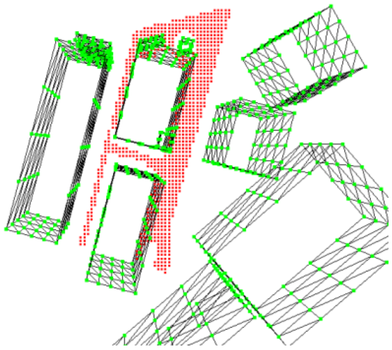


Fig. 8: 3D mesh model of the target scenery

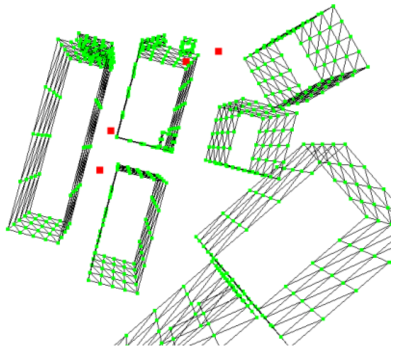


Fig. 9: The optimal layout of four viewpoints

(The building surrounded by candidate viewpoints in Figure 8 is the target.)

6.1 Scan Planning by Proposed Method

First, we have chosen one of buildings in the campus of Kansai University as a target building: we make a scan plan to measure the building and scan it practically in accordance with the obtained scan plan. Figure 7, left shows the target building. As you see, the target building is surrounded with other buildings and the area to set a scanner is comparatively narrow.

Second, we have made a rough 3D mesh model of the scenery around the target and set the candidate viewpoints by using Building Maker by Google. Figure 7, right shows the original mesh model, and we have subdivided the triangles on the surface of the mesh model. Consequently, we have obtained the mesh model of the target area and the candidate viewpoints (Figure 8). The detail of this model is in Table 1.

Table 1: Summary of the mesh model in Figure 8

	# vertices	# triangles
All	706	1124
Target	80	128

candidate viewpoints: 835

Next, we have examined the visibility of the target building and calculated the amount of obtainable data by using the method in Section 4. After that, we have calculated the smallest number of viewpoints to scan all the surfaces of the target building by solving (1): the smallest number of viewpoints to scan all the surfaces of target is equal to 4. Then, we have solved (2) to find the optimal layout of 4 viewpoints, that is, $r = 4$ holds, to maximize the amount obtainable data. The obtained optimal layout is Figure 9. Moreover, the experimental environment which we have used is shown in Table 2. The total calculation time is about 1 minute: the time for the visibility check and calculating the solid angle is 62.63 (sec.), and the times for solving the problem (1) and (2) are 0.01 (sec.) and 0.06 (sec.), respectively.

Table 2: Experimental environment

PC	Lenovo X230
OS	Windows 7 Professional SP1
CPU	Intel Core i7-3520M @ 2.90GHz
Memory	16.0 GB
Optimization Solver	CPLEX 12.5

6.2 On-site Scanning with the Obtained Plan

In accordance with the obtained scan plan, we have scanned the target building by using the 3D scanner LMS-Z420i manufactured by RIEGL.

Figure 10 shows the obtained data by the 3D scanner. This figure is made by merging the data sets which were scanned from the four viewpoints. We can confirm that all the walls of the target building have been scanned. However, there are some obstacles to scan the walls, for example, trees, roofs, circular staircases and so on (Figure 11). Consequently, a part of walls lacks in the data.

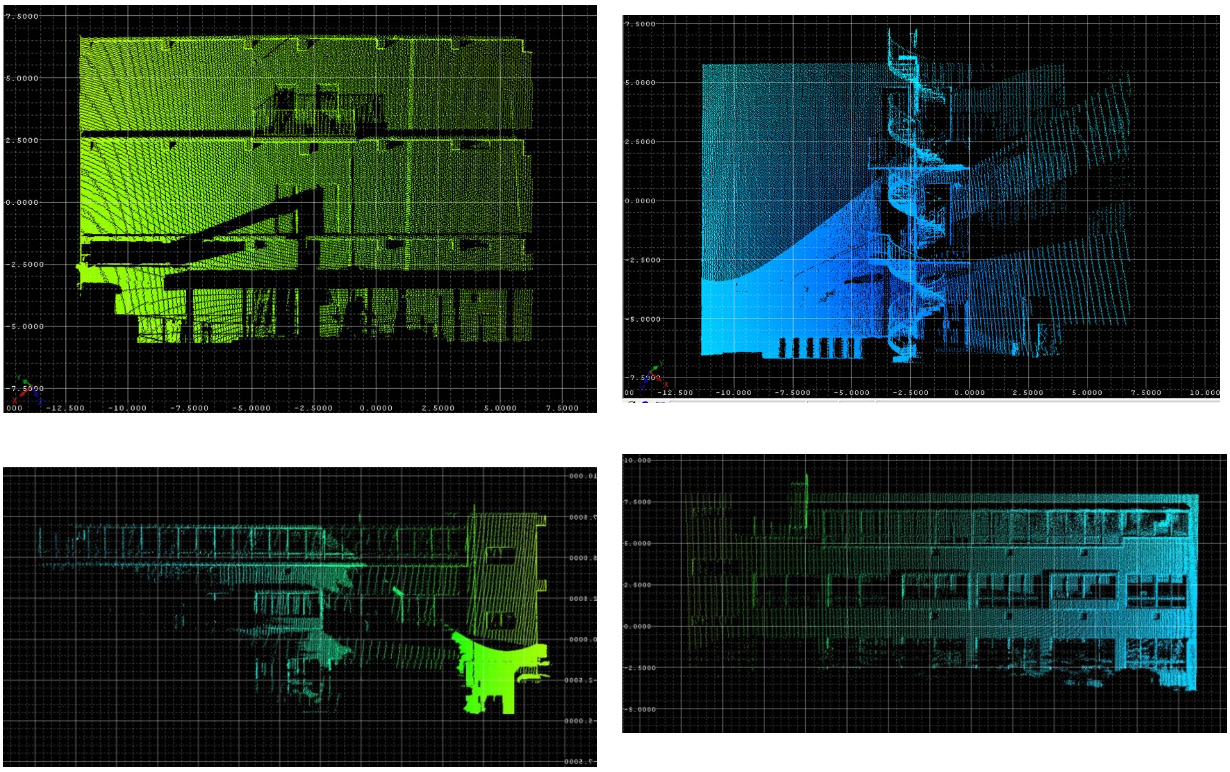


Fig. 10: The scanned data in accordance with the obtained scan plan

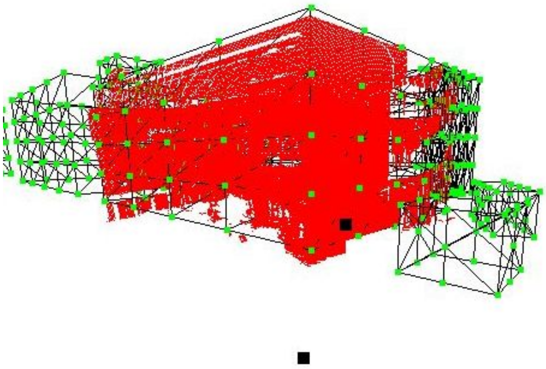
6.3 Discussions

Figure 12 shows that the shape of the building which is obtained by the scanned data roughly coincides with the shape of the mesh model. It ensures that the photogrammetric model is very advantageous for our proposed method.

However, as we can see in Figure 12, the height direction gap between the scanned data and the mesh model is comparatively large. This gap may occur from the height difference of the viewpoints. In this experiment, we have employed Building Maker by Google[2]. Building Maker assumes that the buildings are rectangular solid. Accordingly, it is assumed that the field is level implicitly. On the other hand, the area has some moderate slopes. This is the reason why the height direction gap occurred.

[2] Unfortunately, this sophisticated service is scheduled to be closed on 1 June, 2013.

Fig. 11: On-site photos; there are some obstacles for practical scanning



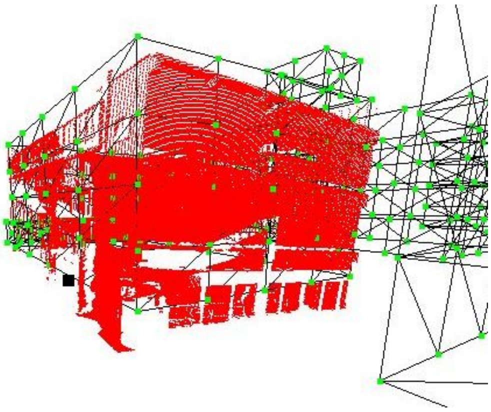


Fig. 12: The scanned data and the mesh model

As we explained above, the scanned data does not cover the target building completely because of obstacles, for example, trees, circular staircases and so on. A straightforward idea to avoid lacking the scanned data is to model the obstacles around the target objects on site. Also, for this purpose, we need some portable interface which can reflect the on-site condition in the rough 3D mesh model.

7. CONCLUSION

In this paper, we proposed a method for making a scan plan for outdoor constructions. Photogrammetric techniques give us a rough 3D model of the target area, and we can calculate the optimal viewpoints by using the model. The optimality of the obtained plan is based on minimization of the number of viewpoints and maximization of the amount of the obtainable data. Moreover, the practical experiment ensures the effectiveness of our proposed method.

8. ACKNOWLEDGEMENT

This work was supported by Japan Society for Promotion of Science (JSPS) Grant-in-Aid for Scientific Research (24510239).

9. REFERENCES

Asai T., Kanbara M. and Yokoya N. (2007). Data acquiring support system using recommendation degree map for 3D outdoor modeling, *Proceedings of SPIE,* Vol. 6491 (doi: 10.1117/12.704292).

Blaer P. S. and Allen P. K. (2009). View planning and automated data acquisition for three-dimensional modeling of complex sites, *Journal of Field Robotics,* 26 (11-12), 865-891.

Dan H., Yasumuro Y., Ishigaki T. and Nishigata T. (2010). Shape Measurement Planning of Outdoor Constructions with Mathematical Programming and Its Applications, *Proceedings of the 10th International Conference on Construction Applications of Virtual Reality (CONVR2010),* 319-328.

Dan H., Yasumuro Y., Ishigaki T. and Nishigata T. (2011). Measurement Planning of Three-dimensional Shape by Mathematical Programming, *Proceedings of the 11th International Conference on Construction Applications of Virtual Reality 2011 (CONVR2011),* 205-216.

Grabowski R., Khosla P. and Choset H. (2003). Autonomous Exploration via Regions of Interest, *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems, 2,* 1691-1696 (doi: 10.1109/IROS.2003.1248887).

Hartley R. and Zisserman A. (2004). Multiple View Geometry in Computer Vision, Cambridge University Press.

Ikeuchi K. and Miyazaki D. (2007). Digitally Archiving Cultural Objects, Springer.

Shibuhisa N., Sato J., Takahashi T., Ide I., Murase H., Kojima Y. and Takahashi A. (2007). Accurate Vehicle Localization using DTW between Range Data Map and Laser Scanner Data Sequences, *Proceedings of the 2007 IEEE Intelligent Vehicles Symposium,* 975-980.

Shih N. and Wang P. (2004). Point-Cloud-Based Comparison between Construction Schedule and As-Built Progress: Long-Range Three-Dimensional Laser Scanner's Approach, *Journal of Architectural Engineering,* 10(3), 98–102.

Shih N. and Huang S. (2006). 3D Scan Information Management System for Construction Management, *Journal of Construction Engineering and Management,* 132(2), 134–142.

Miller P. E., Mills J. P., Barr S. L., Lim M., Barber D., Parkin G. and Clarke B., Glendinning S. and Hall J. (2008). Terrestrial laser scanning for assessing the risk of slope instability along transport corridors, *XXIst ISPRS Congress: Commission V, WG 3,* Beijing, 495-500.

Pitto R. (1999). A Solution to the Next Best View Problem for Automated Surface Acquisition, *IEEE Transactions on Pattern Analysis and Machine Intelligence,* 21 (10), 1060-1030.

Pulli K. (1999). Multiview Registration for Large Data Sets, *Proceedings of Second International Conference on 3-D Imaging and Modeling,* 160-168 (doi: 10.1109/IM.1999.805346).

Surmann H., Nuchter A. and Hertzberg J. (2003). An autonomous mobile robot with a 3D laser range finder for 3D exploration and digitalization of indoor environments, *Robotics and Autonomous Systems,* Vol. 45, No.3-4, 181-198.

Watson C., Chen S., Bian H., and Hauser, E. (2011). LiDAR Scan for Blasting Impact Evaluation on a Culvert Structure, *Journal of Performance of Constructed Facilities,* doi: 10.1061/(ASCE)CF.1943-5509.0000318.

PROCESS ORIENTED NUMERICAL SIMULATION OF MECHANIZED TUNNELLING USING AN IFC-BASED TUNNEL PRODUCT MODEL

Janosch Stascheit & Günther Meschke
Institute for Structural Mechanics, Ruhr University Bochum, Germany

Christian Koch, Felix Hegeman & Markus König
Computing in Engineering, Ruhr University Bochum, Germany

ABSTRACT: *The use of underground space is a prerequisite for maintaining mobility and infrastructure in today's crowded urban areas. In order to minimize risks and mitigate hazards, reasonably accurate numerical simulations of the tunneling process are required. The authors have previously proposed a comprehensive process-oriented 3D finite element simulation model. Information on tunnel projects, however, is usually only available in a heterogeneous and dispersed form, preventing complex simulation models from easily being employed in practice. In this contribution, an IFC-based product model for mechanized tunneling is presented that is used to automatically create a complex numerical simulation model. A model mapping procedure is proposed that links IFC representations of the ground, the tunnel, and the shield machine with the corresponding input of the parametric simulation model. The proposed approach is demonstrated by means of a parameter study for a metro tunnel excavation in Düsseldorf, Germany.*

KEYWORDS: *Mechanized tunneling, Numerical simulation, Product modeling, IFC, Data exchange*

1. INTRODUCTION

The increasing demand for the use of underground space has been fostering the tunneling industry in recent years. With more challenging projects, also the demand for advanced numerical simulation tools for the prediction of tunneling-induced ground movements and possible hazards for surface structures has increased.

A comprehensive 3D finite element simulation model accounting for partially saturated soil, segmented tunnel lining, tail void grouting, a deformable shield skin and thrust/steering jacks has been preliminarily proposed by the authors (Meschke et al. 2011). Such complex simulation models, however, require a large amount of project-specific information that is usually available from dispersed resources such as drawings, spreadsheets, diagrams or heterogeneous databases. For this reason, complex numerical analyses are still not commonly employed in current practice.

In this contribution, a unified, IFC-based product model for mechanized tunneling is presented that is directly linked to the numerical simulation software. The IFC tunnel product model basically features three sub-domains: the ground, the tunnel, and the shield machine. Based on that, the simulation model can automatically be created and invoked. The advantage of this automated simulation procedure is the on-the-fly generation of new simulation results for any given changes in specifications or data such as updated design, deviations in ground conditions, occurrence of hazards, and disruptions in the tunneling workflow. Finally, the product model and its link to the FE simulation software are demonstrated simulating the excavation process of a metro tunnel in Düsseldorf, Germany.

2. BACKGROUND

2.1 Current practice

In mechanized tunneling, design documents are usually available in many different formats and databases. Furthermore, the type of data differs widely (e.g. CAD drawings, text reports, spreadsheets and diagrams). This complicates the generation of Finite Element (FE) simulation models, because required data has to be organized from multiple resources, and documents have to be searched for appropriate parameters. Additionally, these

Citation: Stascheit, J., Koch, C., Hegeman, F., König, M. & Meschke, G. (2013). Process oriented numerical simulation of mechanized tunnelling using an IFC-based tunnel product model. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

parameters usually have to be manually integrated and updated in case of design changes. Thus, in tunneling practice, numerical simulation is still not used to the extent that the possibilities of current simulation models would suggest. This is mainly due to the enormous effort in the manual modeling process and, in particular, in the procedure of gathering all available information on the project in a form that can be easily adopted for the model generation (Guglielmetti et al. 2008).

2.2 Current research efforts

2.2.1 Numerical simulation in mechanized tunneling

Guglielmetti et al. (2008) have suggested applying realistic numerical simulations for the computation of settlements to accurately predict the influence of the tunnel construction on the built environment. For the generation of realistic numerical models, linking CAD tools and numerical simulations has become a popular issue in recent years. In particular in industrial design, this has become state of the art, for example in the automotive sector, and is a matter of ongoing research (Franciosa et al. 2013). For geotechnical applications, Liao et al. (2005) have developed an interface for transforming geological profiles into finite volume models in FLAC3D by means of the ANSYS pre-processor. In an attempt to incorporate site-acquired monitoring data in the validation and improvement of numerical simulations of the shield tunneling process, a tunnel information system has been developed by Chmelina and Rabensteiner (2010). This system is currently being coupled with a process-oriented FE simulation software for mechanized tunneling and that is also employed in the current work. An automated modeling tool (Stascheit et al. 2008) acts as one of the core modules in order to accomplish seamless generation of parameterized simulation models. However, none of these approaches to date has integrated a unified product model that contains the complete design data of a mechanized shield tunneling project with a numerical simulation tool.

2.2.2 Product modeling in mechanized tunneling

Building Information Modeling (BIM) is an up-to-date modeling concept involving the generation and the management of a three-dimensional (3D) digital representation of physical and functional characteristics of a building or construction facility during its entire life-cycle. Building information models are commonly used as shared data and knowledge resources to support planning, construction, management, utilization, revitalization, and demolition activities (Eastman et al. 2008). BIM is often associated with the Industry Foundation Classes (IFCs), which are a data structure for representing complex building information. The IFCs have been developed by buildingSMART as a neutral, non-proprietary and open standard for sharing BIM data (Eastman et al. 2008). Currently, the IFC standard predominantly supports building constructions rather than tunnel construction. There are initiatives to extend this standard and develop an IFC-based model for shield tunnels (Yabuki 2008) and shield machines (Hegemann et al. 2012). However, there is no integrated model available that captures all information necessary to fully derive a FE simulation model.

3. METHODOLOGY

The overall approach is depicted in Figure 1. Within the first step, project relevant data available from dispersed resources are combined and integrated into a holistic product model for mechanized tunneling. Obviously, the creation of the product model takes a significant amount of time which has to be contrasted with the amount of time gained by the automated model generation and mapping process. Moreover, the product model can be used for generating multiple simulation models for different simulations, for example, driving simulation, grouting simulation and advance exploration simulation as well as for the overall data management within the life-cycle of the entire project (Eastman et al. 2008).

For generating the holistic product model we use and extend the IFC. Based on that, the FE simulation model is automatically generated using an ontology-based mapping approach. The focus of this contribution, as highlighted in Figure 1, is on the definition of the IFC tunnel product model (TPM) and the automated model mapping of its properties to the FE simulation model.

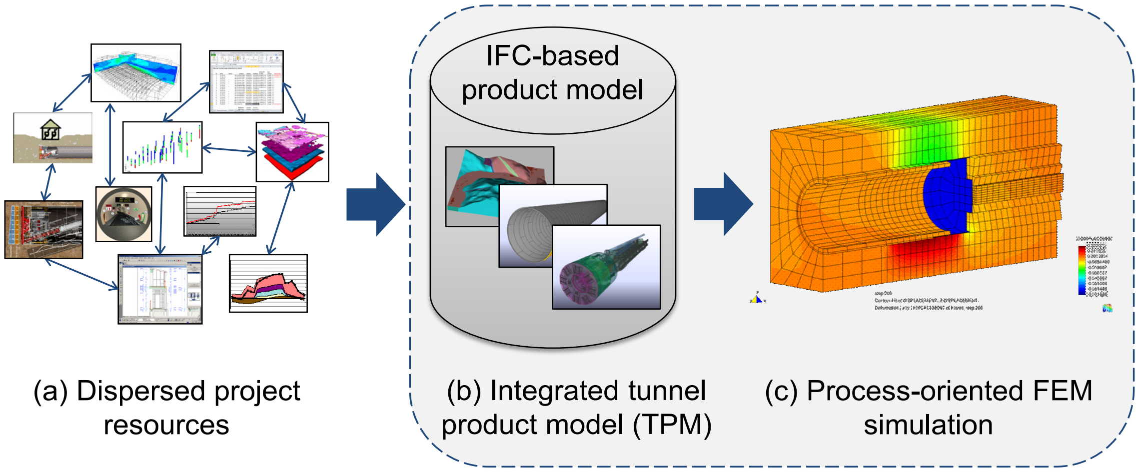


Fig. 1: Method overview (paper focus emphasized).

3.1 IFC-based tunnel product model (TPM)

To achieve a holistic product model an IFC-based approach is applied. It enables the link between individual objects of the model and captures both geometric representation and semantic information of an object. Furthermore, by generating an object-oriented data model an efficient structure can be provided to capture the different data types in a tunneling project. To cover all required information in mechanized tunneling, the holistic IFC product model consists of three partial models: the ground data model (GDM), the tunnel model (TM), the tunnel boring machine model (TBM), for now neglecting a model of the built environment (Fig. 2).

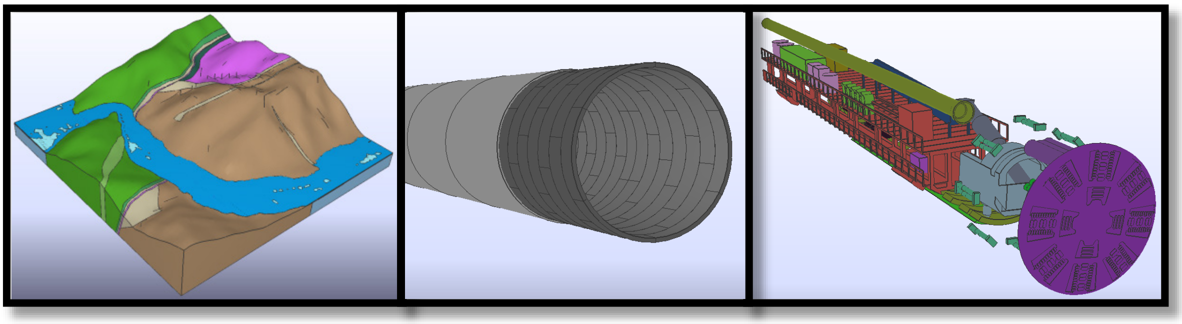


Fig. 2: Components of the proposed IFC tunnel product model: (a) the ground data model (GDM), (b) the tunnel model (TM), (c) the tunnel boring machine model (TBM).

In general, the GDM stores subsurface information including the shape of a ground layer and its material parameters. The TM captures information on the tunnel alignment, the lining segments, and the annular gap grouting. The TBM contains information about the dimension and the characteristics of each individual shield machine component, for example, the shield and the thrust jacks. Due to the missing extensions of the IFC regarding ground data, objects of the GDM are represented as IFC proxies. A proxy class is a generic container defined by its associated geometric and semantic properties (BuildingSMART 2011). For example, if a ground layer should be stored, a new proxy element is added to the partial ground model. The proxy has attached both a geometric representation defining the region of the layer and semantic information on the material properties by means of so-called property sets.

On the other hand, the TM is designed based on an approach recently presented by Borrmann and Jubierre (2013) (Fig. 3b). It provides individual classes to model different aspects of a tunnel, for example, the lining (*LiningSpace*), the segmental rings (*IfcRingSegments*), and the annular gap grouting (*AnnularGapSpace*). Each provided class can have attached both a geometric representation defining the geometric boundaries of its respective element and semantic information to characterize its properties by means of so-called property sets.

For the TBM, a similar approach has been previously presented by the authors (Hegemann et al. 2012) (Fig. 3a). Here, the IFC are extended for the purpose of describing the geometry (e.g. the dimension of the shield and the cutting wheel), the semantics (e.g. material properties and manufacturing information) as well as the process information (e.g. performance and operating data) of a tunnel boring machine. In accordance with the TM, the TBM can be divided into two parts, the spatial and the element part. The spatial part contains new classes to describe the spatial structure of the TBM, needed, for example, by visualization components (e.g. *IfcTbmHead*). The element part, on the other hand, specifies certain elements needed to describe the operation and behavior of a boring machine (e.g. *IfcTbmCuttingWheelElement*).

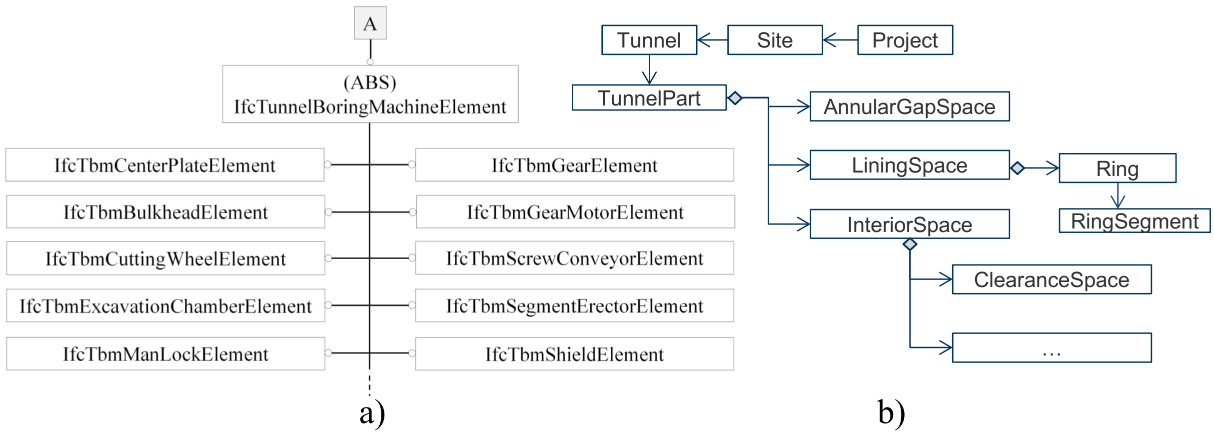


Fig. 3: IFC extensions: (a) classes for the TBM (Hegemann et al. 2012), (b) classes for the TM (Borrmann and Jubierre 2013)

3.2 Process-oriented Finite Element simulation

Mechanized tunneling comprises various process components such as the excavation of the ground, the advance of the shield machine, the installation of lining segments and the grouting of the annular gap evolving behind the shield. Furthermore, construction measures like heading face support by means of earth muck or support fluids play an important role. The process-oriented FE simulation model employed in this contribution has been developed in the attempt to account for all relevant components of the shield tunneling process with the required level of detail to cover their effects on structural loading in the tunnel as well as the impact of the tunnel excavation on the surroundings. Details of the model and its implementation can be found in (Meschke et al. 2011).

Since the manual generation of complex FE simulation models is a very time-consuming and error-prone task and in order to allow for a direct link of the simulation model with a tunnel product model, the model components have been combined to a parameterized model that can be created by means of an automated preprocessing tool (Stascheit et al. 2008). Figure 4 depicts the main geometrical parameters of the simulation model that have to be assigned by the model mapping scheme. Based on these parameters, a numerical simulation model instance can be automatically generated and executed.

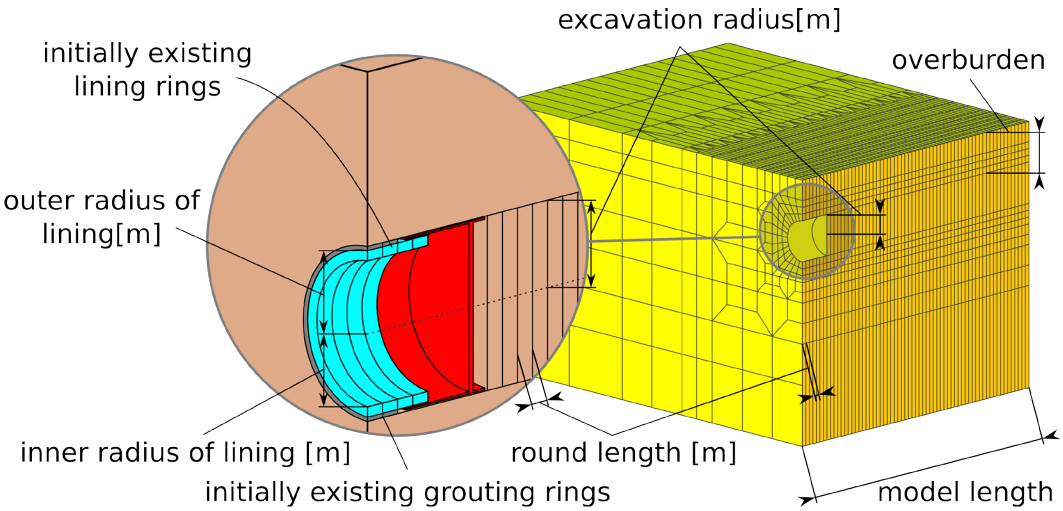


Fig. 4: Geometrical parameters of the FE simulation model.

3.3 Automated model mapping

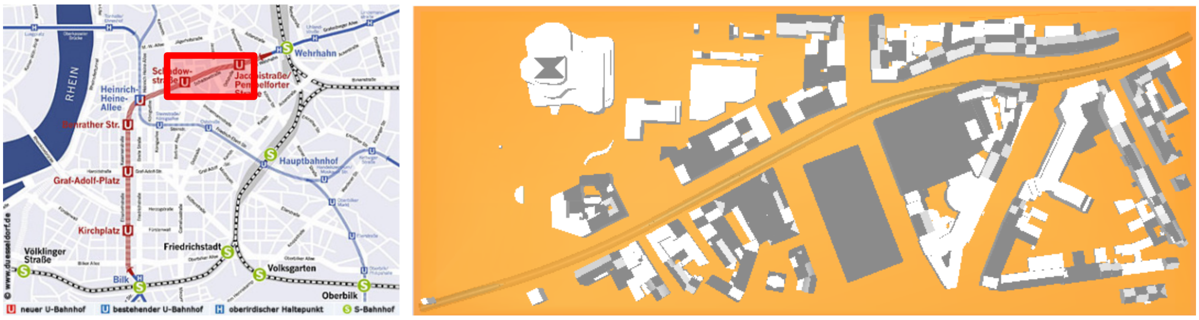
Automated mapping between different models always implies the problem of a different nomenclature of identical parameters within individual models. For example, the porosity of a ground layer is called “layer_porosity” within one simulation model, but “porosity” in another one. Therefore, a mapping is necessary defining that these different expressions describe identical parameters. Ontologies are commonly used to solve this problem. They create a pool of ordered terms, restrictions and rules to formally describe objects and their interrelations. For our purpose, an own XML-based ontology schema has been developed. This schema establishes a connection between the different parameter names of the simulations by assigning an umbrella term. Additionally, both the resource location of the parameter value inside the TPM and the target location inside the parametric simulation model are stored for automated data reading and writing, respectively.

However, the mapping of required parameter values from the TPM is a challenging task and can be divided into two categories. In the first category, the required parameter value is available in the TPM, exactly as needed. In the second category, the product model does not contain the requested value directly, because the partial models only contain raw information provided by several design parameters. In this case, pre-defined algorithms referring to existing parameters in the TPM are employed for calculating required values. For example, the overburden of the tunnel is needed at a specific position of the tunnel lining. Therefore, an algorithm calculates the distance from the tunnel lining (TM) at the specific position to the ground surface based on the ground geometry (GDM)

4. IMPLEMENTATION AND CASE STUDY

The proposed IFC based tunnel product model has been implemented using the Open IFC Tools (Open IFC Tools 2012). The process-oriented FE simulation model has been implemented in the open source multi-physics finite element framework KRATOS (Davdand et al. 2010). This tool has been chosen due to its open modeling interface. However, also any other FE framework which allows the generation of simulation models by using input files can be applied. For geometrical modeling, meshing and assignment of boundary conditions, the customizable pre- and post-processor GiD (www.gidhome.com) is employed. A collection of Python scripts is used to batch-control GiD and to prepare the model data for the simulation. The model mapping has been implemented by means of XML schemas.

To demonstrate the capabilities of the proposed model mapping technique, a tunnel excavation in Düsseldorf, Germany has been modeled using the tunnel product model (Fig. 5). The complete project, running from 2007 till 2014, comprises 2.3 km of shield driven tunnels and various deep excavations. Figure 5a shows a city map of Düsseldorf with the complete alignment of the new tunnel. The extract applied and modeled for this case study is highlighted in Figure 5b. It has an approximate size of 724 x 282 x 77 m with a tunnel length of 780 m at a tunnel diameter of 9.4 m.



a) b)

Fig. 5: Case study: (a) map of Düsseldorf, (b) the IFC model visualized.

Based on the project data, a case study has been performed varying two design parameters: the overburden and the support pressure. The former is a geometrical parameter defining the depth of the tunnel whereas the latter is a semantic process parameter defining the amount of heading face support. Figure 6 illustrates the variation of the overburden parameter. Case a) is a shallow tunnel with an overburden of 1.5 diameters while case b) is a deeper tunnel with an overburden of 2.5 diameters. In the first step, a respective box is cut from the global representation of the tunnel product model. Step 2 shows the discretized FE model as a result from the model mapping procedure. In step 3, the simulation results in terms of surface settlements resulting from the excavation are shown. For the deeper tunnel, the support pressure has been varied: one setup has been run with a support pressure that is equal to that of the shallow situation (180 kPa); another setup features an adequately increased support pressure for the deeper tunnel (280 kPa).

The effect of the variation of the two exemplary model parameters is shown in Figure 7. The right plot shows the evolution of the settlements directly on top of the tunnel axis in a fixed monitoring section. As the shield approaches the monitoring section, the settlements are increasing. They reach a maximum after the shield has passed and the annular gap is fully grouted. Finally, the settlements remain constant. The left plot depicts the transversal settlements at three different stages 12 m ahead and behind the shield and as the shield is passing the monitoring section, respectively. From these plots the influence of the two investigated parameters can be seen. The depth of the tunnel has the largest influence on the surface settlements, whereas the support pressure only has a minor impact in this example.

5. CONCLUSION

In recent years, increasing demand for the use of underground space has been fostering the tunneling industry resulting in the need for advanced numerical simulation tools for the prediction of tunneling-induced ground settlements. In this contribution, a unified, IFC-based product model for mechanized tunneling was presented that is directly linked to the numerical simulation software.

The IFC tunnel product model basically features three sub-domains: the ground, the tunnel, and the shield machine. Based on that, the numerical simulation model can automatically be created and invoked. The presented case study revealed the advantages of the proposed approach. Simulation results could be easily obtained for two exemplary parameter variations. This shows the potential to conveniently perform simulation-based predictions for any given changes in specifications or updated designs without the need for manual re-editing of complex FE simulation models.

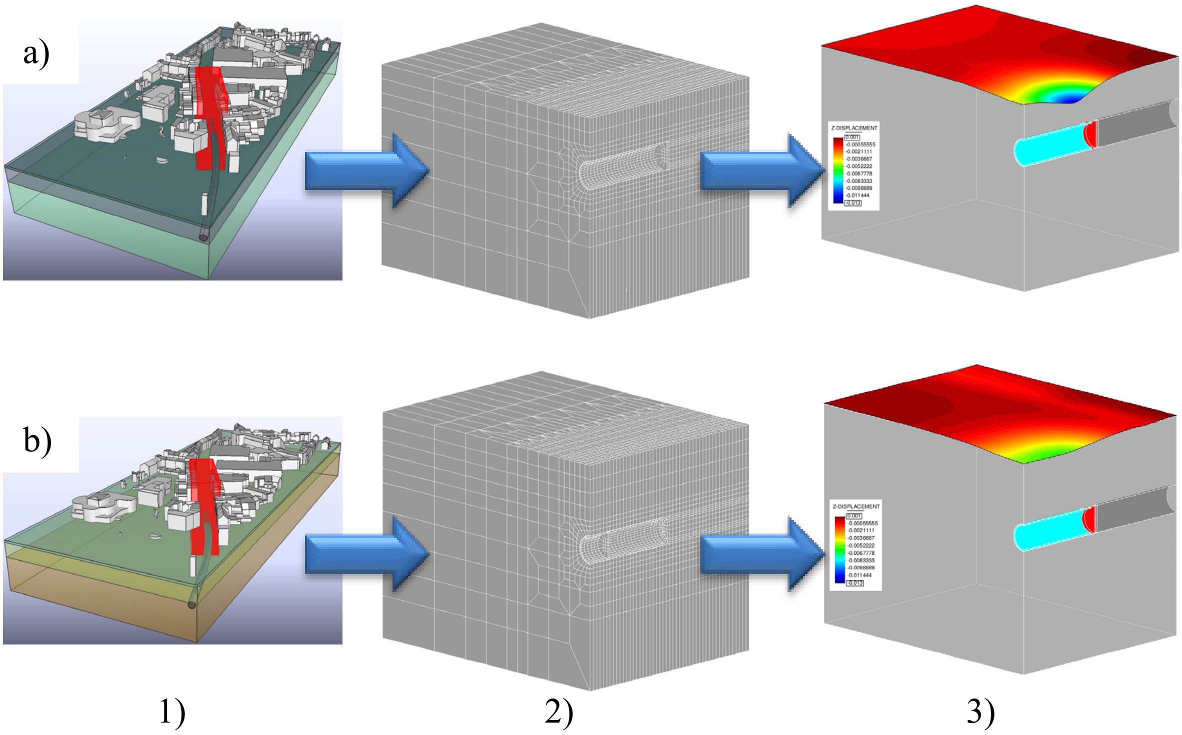


Fig. 6: Workflow (steps 1 to 3) of model mapping for an overburden of 1.5D (a) and 2.5D (b).

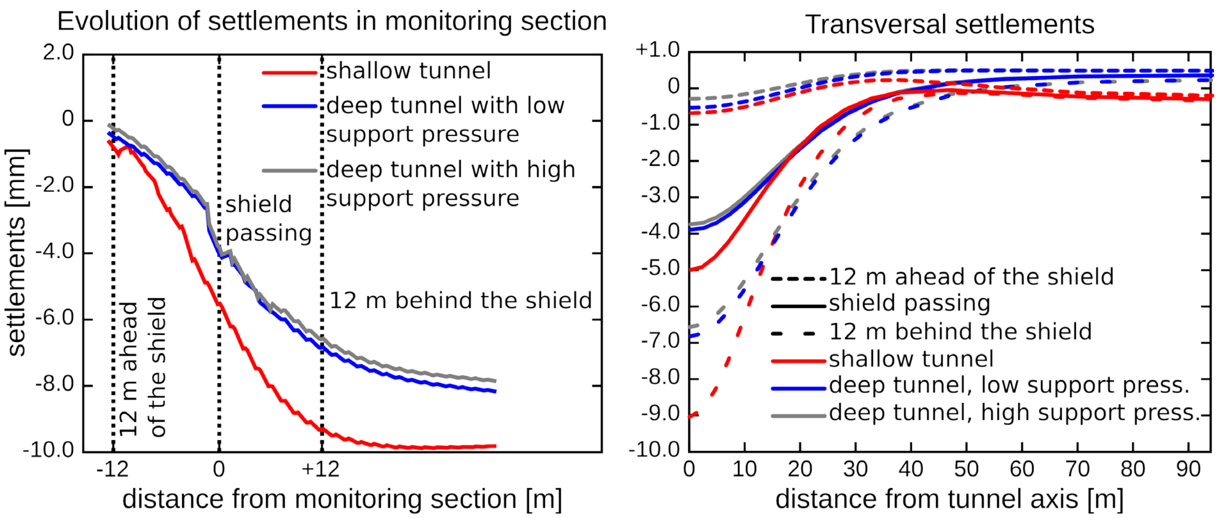


Fig. 7: Evolution of settlements in the investigated tunnel variants.

6. REFERENCES

Borrmann, A., and Jubierre, J., (2013) "A multi-scale tunnel product model providing coherent geometry and semantics", In *Proc. of the Int. Workshop on Computing in Civil Engineering 2013*, Los Angeles, USA

BuildingSMART. (2011). Industry Foundation Classes (IFC) - The buildingSMART data model. http://www.buildingsmart.com

Chmelina, K., and Rabensteiner, K. (2010). "Improvement of the safety and profitability of tunnel drives through the use of automated measurement and alarm systems – examples in practice". *Geomechanics and Tunnelling* 3, 215–224

Dadvand, P.; Rossi, R., and Oñate, E. (2010). "An Object-oriented Environment for Developing Finite Element Codes for Multi-disciplinary Applications". *Archives of Computational Methods in Engineering*, 17, 253-297.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2008). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers. Wiley & Sons, Inc. New Jersey, US.

Franciosa, P., Gerbino, S., Lanzotti, A., and Silvestri, L. (2013). "Improving comfort of shoe sole through experiments based on CAD-FEM modeling". *Medical Engineering & Physics*. 35(1):36-46.

Guglielmetti V., Grasso P., Mahtab A., and Xu S. (2008). Mechanized Tunneling in Urban Areas, Taylor & Francis Group, London, UK.

Hegemann, F., Lehner, K., and König, M. (2012). "IFC-based product modeling for tunnel boring machines", In *Proc. of the 9th European Conference on Product and Process Modelling*, Reykjavik, Iceland.

Liao, Q.L., Zeng, Q.B., Liu, T., Lu, S.B., and Hou, Z.S. (2005). „Automatic model generation of complex geologic body with FLAC 3D based on ANSYS Platform [J]". Chinese Journal of Rock Mechanics and Engineering, 6.

Meschke, G.; Nagel, F., and Stascheit, J. (2011). "Computational Simulation of Mechanized Tunneling as Part of an Integrated Decision Support Platform". *Journal of Geomechanics (ASCE)*, 11, 519-528

Open IFC Tools (2012), Open IFC Tools – Processing, Visualization, 4D, www.openifctools.com

Rebolj D., Tibaut A., Čuš-Babič N., Magdič A. & Podbreznik P. (2008). "Development and application of a road product model". *Automation in Construction*, 17, pp. 719 – 728

Stascheit, J.; Nagel, F., and Meschke, G. (2008). „Automatic web-based numerical modelling of shield tunneling". *8th World Congress on Computational Mechanics (WCCM8)*, Venice, Italy.

Yabuki N. (2008). "Representation of caves in a shield tunnel product modeling". In *Proc. of the 7th European Conference on Product and Process Modeling*. Sophia Antipolis, France.

OCCLUSION METHOD BASED ON THREE-DIMENSIONAL FEATURE DATA FOR MOBILE AUGMENTED REALITY APPLICATIONS[1]

Hiroki Ito & Koji Makanae
Miyagi University, Japan

ABSTRACT: *In recent years, the demand for augmented reality (AR) applications has been increasing owing to the spread of smartphones equipped with cameras and various sensors. Hence, there is a need for a high-speed processing method to build three-dimensional (3D) AR applications on mobile devices. In particular, an occlusion process, which determines the virtual object to be drawn on the real image, is indispensable. However, this process requires dynamic depth data of objects in real and virtual spaces in accordance with the movement of the camera. In this paper, we developed an AR tsunami simulation, which uses an occlusion method that cuts out a virtual water-wave by the 3D feature model obtained from real space. The application was developed by using the Unity game engine, which provides realistic rendering functions and compatibility with various sensors in smartphones with an occlusion program that uses OpenGL shader. As a result, the developed AR application performed the occlusion process without sacrificing processing power.*

The development of AR applications requires careful consideration of processing speed and accuracy in accordance with the requirements of presentation. The visualization of tsunami waves should also be improved; for example, sprays of wave collision should be represented.

In the future, development of a more realistic representation technique and a simple method to retrieve depth data dynamically from real space will be necessary.

KEYWORDS: *Augmented Reality, Occlusion, OpenGL, Smartphone, Game Engine.*

1. INTRODUCTION

Augmented reality (AR) technology, a technique that can present information effectively, has attracted wide attention in various fields such as construction, education, entertainment, and health care.

In comparison with virtual reality (VR) technology, the advantages of AR are that it is unnecessary to prepare 3D models that correspond to real space and that it enables an intuitive understanding because it adds information to real space.

Kakuda et al. (2007) developed a “Virtual Asukakyo” system that enables one to view restored ruins in an outdoor environment by using AR technology. The system superimposes the ruins reproduced in computer graphics (CGs) on the physical space by examining where they existed with head-mounted display (HMD).

Meng et al. (2012) developed an AR system that aids the understanding of human anatomy by using Microsoft’s RGB-D camera “Kinect” to track the skeleton of a person and superimpose the internal image of the human body as if seen in an X-ray camera.

In recent years, the demand for AR applications is increasing with the spread of mobile terminals including smartphones. Smartphones, which make a significant contribution to the spread of AR technology as portable hardware devices, can retrieve external information from GPS, cameras, and various sensors to present information intuitively by touch displays and speakers.

However, a high-speed processing technique is required to implement AR expression with high accuracy on mobile devices. In particular, occlusion processes are indispensable for superimposing objects of virtual space

---

[1] Citation: Ito, H. & Makanae, K. (2013). Occlusion method based on three-dimensional feature data for mobile augmented reality applications. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

onto physical space. High processing power is required to calculate dynamic depth data in accordance with the movement of a camera.

In this paper, we propose and verify occlusion methods of virtual objects on smartphones by registration through the use of existing real space information. We also describe the experimental results of an AR tsunami simulation by using a game engine to validate this method.

2. OCCLUSION IN AR SCENES

2.1 Occlusion problem

Occlusion processes are required to represent the positional relationships between virtual and real objects in AR. Figure. 1 shows an example of occlusion images. Figure 1(a) and (b) show the AR images from a camera positioned in bird's eye view. In (a), reality has been impaired by the virtual blue cylinder object displayed in front of the real building because the positional relationship is incorrectly expressed. In contrast, (b) correctly represents the positional relationship because the cylinder clipped according to the shape of the building. Depth information in real space is required to correctly superimpose the virtual object, as shown in (b).

2.2 Occlusion methods and challenges

Suyang and Vineet. (2010) studied a robust occlusion method that uses real-time Time-of-flight (TOF) camera data to correctly resolve the depth of real and virtual objects in AR images. Obtaining high-accuracy depth information without being affected by the environment is possible by using LiDAR and ToF cameras. However, these methods cannot take advantage of the portability of a smartphone because a depth camera must be carried and set up.

The methods for acquiring depth information by image processing procedures such as pattern matching do not require additional hardware other than smartphones. However, the smartphones do need high processing power. Image processing is also difficult to use on smartphones because it is strongly influenced by outdoor environments.

The aim of this research is to present a method for solving the occlusion problem of AR by aligning the virtual and real objects in virtual space by using existing spatial information (e.g., created, for instance, by aerial surveys) to take advantages of the convenience portability of smartphones.

3. RESOLUTION OF OCCLUSION PROBLEM BY USING GEO LOCATION

3.1 Combining 3D models and registration

In the first phase, the proposed method constructs a virtual space to simulate the occlusion of virtual objects by real objects. Figure 2 shows the relations between the virtual and real spaces. The virtual space contains real objects as feature information of real space, virtual objects as additional information to be superimposed, and a viewpoint as user's position in real space.

Real objects are composed of their geographic coordinates and 3D model data that represent the shape of the feature in real space. These objects are located in the virtual space at a position based on its geographic coordinates; the occlusion of virtual objects is processed by the 3D model data.

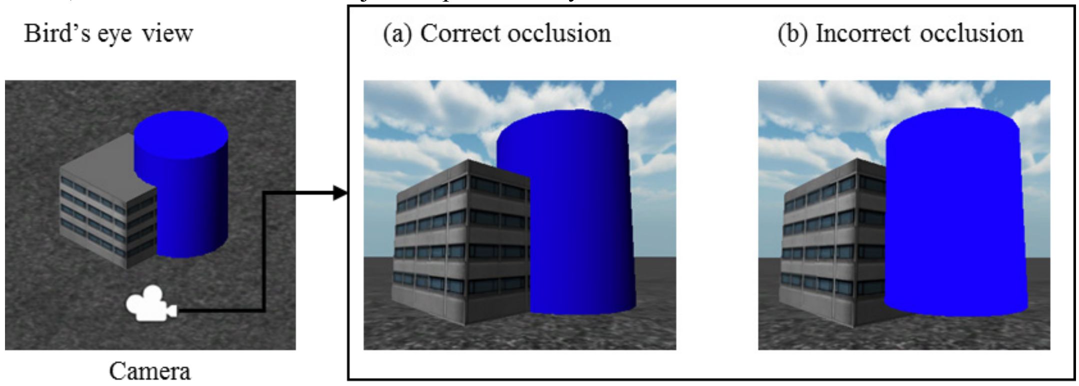


Fig. 1: Examples of incorrect and correct occlusion in AR scene

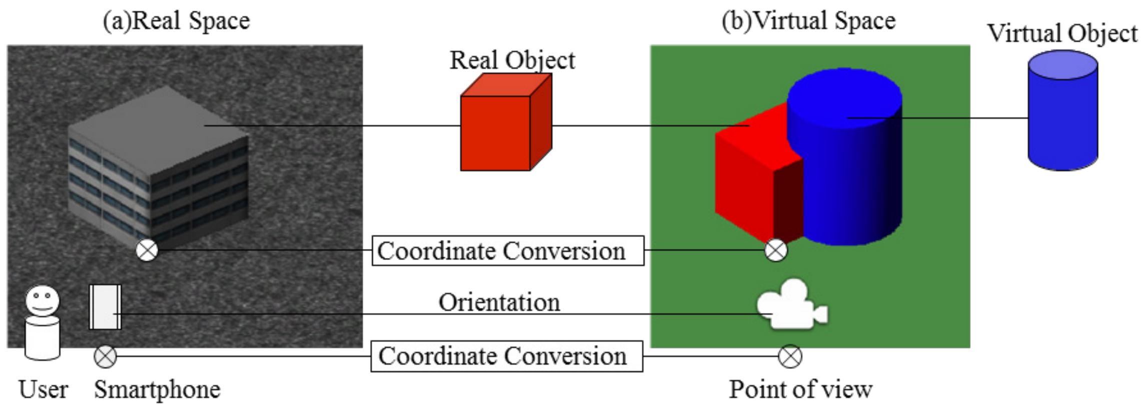


Fig. 2: Construction of virtual space

The position of a viewpoint in the virtual space is determined on the basis of the geographical coordinates acquired by the GPS sensor of the smartphone. The orientation of a viewpoint is updated on the basis of the angle and direction of the smartphone camera, which is obtained from the acceleration, magnetometric sensor, gyro sensors, and so on.

The geographic coordinates obtained from the GPS sensor must be translated to CG coordinates to place real objects and the viewpoint based on real space positions. A virtual object is positioned anywhere; depending on its information, however, coordinate conversion is performed as well to specify its position by geographic coordinates.

The movement of the user (smartphone) in real space can be expressed by that of the viewpoint in the virtual space. AR expression and occlusion in accord with the video image for each frame can be performed by updating the parameters of the viewpoint on the basis of the orientation information for the camera and GPS coordinates.

3.2 AR system using a smartphone

Figure 3 shows a hardware diagram of the AR system involving the use of a smartphone. The AR system is installed as an application to the smartphone. The application updates the orientation and position of the viewpoint in virtual space by obtaining the orientation from various sensors and the geographical coordinates from the GPS. The application obtains frame-by-frame video images of the physical space taken by the camera to display the AR Image and superimposed virtual objects simultaneously.

3.3 Generation of AR Images

Figure 4 shows the processing flow of rendering AR images. (c) is an example of a rendered image of the virtual space from a viewpoint. (a) and (b) are images of rendered real and virtual objects respectively. The occluded mask image shown in (d) can be obtained by extracting a part of the virtual object from (c). In the final step, (d) is superimposed on (e), which is obtained from the smartphone camera, to create the AR image (f).

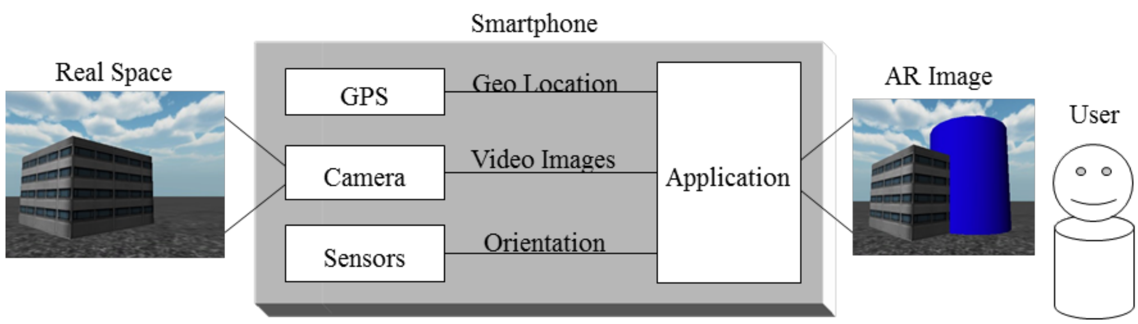


Fig. 3: Diagram of an AR smartphone system

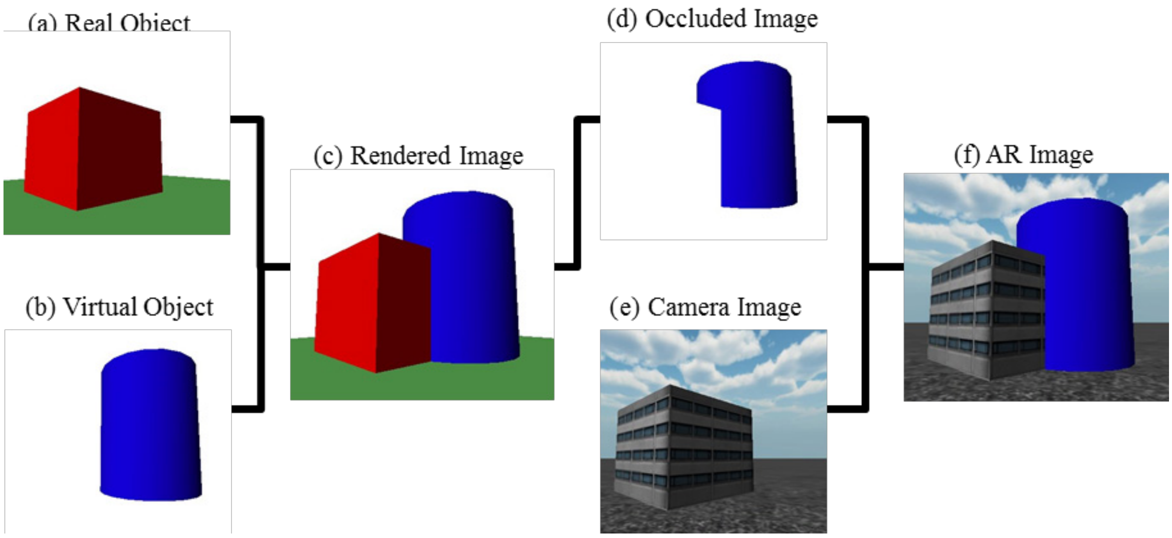


Fig. 4: Processing flow of rendering AR images

4. USE OF UNITY GAME ENGINE TO BUILD AR APPLICATION FOR SMARTPHONE

4.1 Tsunami Simulation Application

In this study, we developed a tsunami simulation for the Android operating system (OS) to evaluate the method described in the previous section. This simulation has been developed for simulating tsunami. By superimposing a tsunami CG as a virtual object on real space, it displays a tsunami image when the user is standing in the flooded area.

We used Google Nexus7 as an alternate device of smartphone. We also used the Unity 3.5 game engine and Android SDK as the development environment.

4.2 Construction of flood virtual space

The first step is to place existing feature models and a viewpoint in a virtual space by using the geographic coordinates obtained from the GPS of the smartphone.

We made feature models from cartographic information and acquired geographic coordinates as the real objects. If the geographical coordinates of a model exist, its position can be adjusted accordingly. Table 1 shows the conversion of each coordinate system. The application converts WGS84 coordinates obtained from the GPS to the Japanese plane rectangular coordinates, which in turn are converted to CG coordinates in the game engine. We included feature model data in the application on a trial basis in this time. The application reads the feature model data as real objects and convert the geographic coordinates to CG coordinates to place them in virtual space.

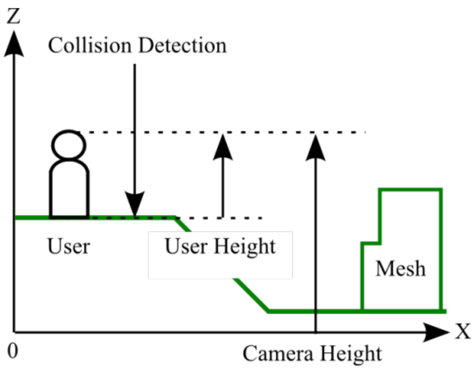


Fig. 5: Conversion of altitude

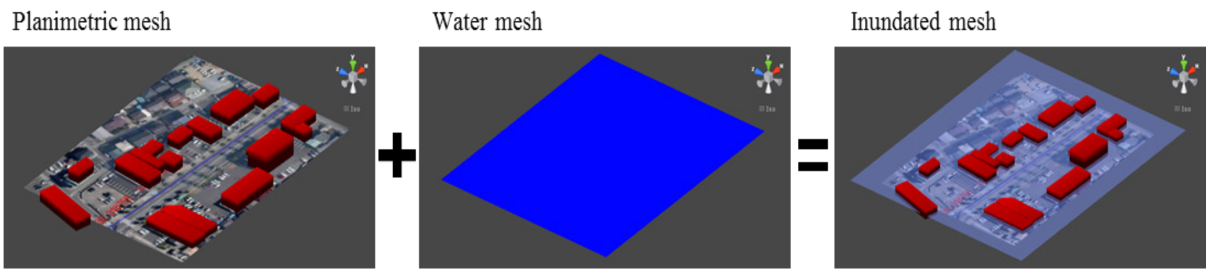


Fig. 6: Composition of planimetric mesh and wave mesh

A viewpoint is located in virtual space after the coordinates are converted as well as the feature objects. The position of this viewpoint is constantly updated to match the movement of the user in real space. In addition, its orientation is updated constantly based on the various sensors of the smartphone. Thus, the pointing direction of the smartphone camera in real space and the direction of the viewpoint in virtual space are matched. Figure 5 shows conversion of the height of the viewpoint. First, we calculate the height of the viewpoint by performing collision detection for a feature mesh on the axial height of the current position. Subsequently, we calculate the height of the viewpoint by adding a user-specified height to mesh height.

The application then places the virtual wave model in virtual space. The wave model is a simple plane mesh, as shown in Fig. 6. It expresses the simulated flood height by moving the wave model at an altitude specified by the user. By combining the wave mesh and feature mesh as shown in Fig. 6, the application can create a flood image clipped by real objects. These models are used in the occlusion process to create the final AR images.

4.3 Occlusion process and rendering

The application creates AR images by using video images and a constantly updated virtual space image. A rendered image (e.g., Fig. 7) can be obtained by rendering the flood model from the viewpoint. In this image, the wave model as virtual object is clipped by the feature mesh. This result is the same as that of virtual objects

Table 1: Coordinate conversion

WGS	Japan PRCS	Unity
Latitude	X	Z
Longitude	Y	X
Altitude	-	Y

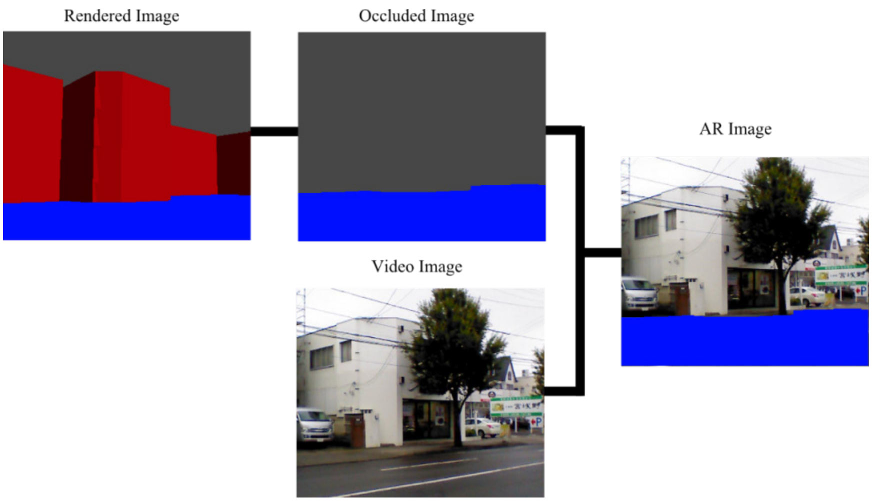


Fig. 7: Superimposition of occlusion image on video image

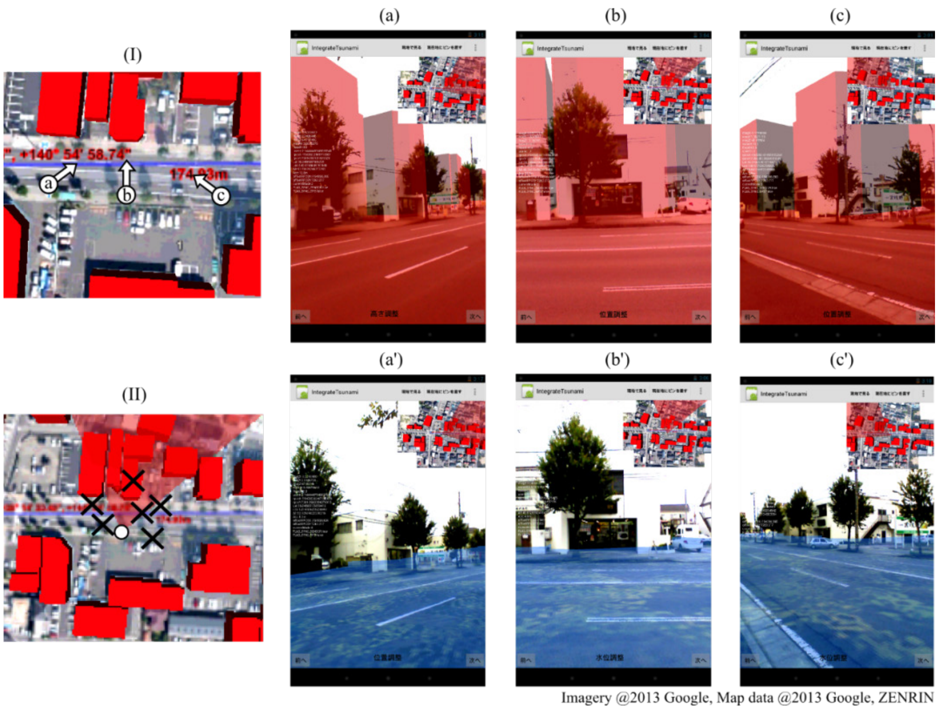


Fig. 8: Application images

occluded by objects in real space. The occluded image is obtained by extracting a portion of this wave model.

We created an occlusion shader by using OpenGL shader to mask the feature model on the game engine. The pixels that draw the models by using the occlusion shader copy the background video image instead of drawing its model. By specifying the occlusion shader to apply to the feature models, an AR image masked by feature models can be obtained, as shown in Fig. 7.

4.4 Validation and results

Figure 8 shows AR images of the actual application screen. Image (I) is a top-down view of the feature mesh. The arrows indicate the position and direction of the camera which took images (a), (b), and (c). In image (a), (b), and (c) the real objects to clip the virtual objects are drawn as transparent meshes. Image (a'), (b'), and (c') are final AR images with superimposed waves clipped by buildings. Figures represent the virtual objects moving in response to movement of the camera position.

As a result, position misalignment has occurred. Image (II) shows an example of misalignment. The cross marks indicate the positions that are obtained by GPS while taking AR image (b). The circle mark indicates the actual position where the AR image was taken. Also, misalignment of camera orientation has occurred owing to attitude sensors. Figure 9(a) represents an example of misalignment of camera orientation. In order to solve these misalignments, a function of on-site manual adjusting is added to the application. Figure 9(b) shows an example image after adjusting the position. An automatic adjusting method should be developed in the future work.

5. CONCLUSION

In this paper, we described a method of occlusion processing by using existing spatial information to register on the smartphone. We also developed a tsunami simulation to evaluate this method. As a result, an application involving use of the occlusion process operated at a speed tolerable even on smartphones. We confirmed that the advantage of this method is its ability to handle occlusion in AR by using only a smartphone to eliminate the need to provide additional hardware (e.g., an RGB-D camera). Furthermore, the method could be used while moving by constant updating of the location information in GPS.

One problem was that the method resulted in impairing the AR for occlusion handling of dynamic objects such as people or vehicles. Furthermore, occlusion handling of small objects such as trees and utility poles was not performed. A possible solution to those problems is to uses a combination of existing data for large objects and distance sensor data for small objects.

Problems in understanding occurred because the tsunami application provided only AR images in the first-person view. This hampers the user's ability to understand their situation (e.g., flood level, position). Continued investigations on information presentation methods that are easier to express in AR images (e.g., using VR as well as AR to provide information on this issue) will be necessary.

We entered 3D model data in the application to enable reading on a trial basis in this study. In future work, we will continue to improve this application so that is can be used anywhere by obtaining the model data dynamically through a network. In addition, consideration of how existing model data are used and stored for this application is necessary.

6. REFERENCES

Meng, M. (2012), Augmented Reality Magic Mirror using the Kinect. Technische Universität München. http://campar.in.tum.de/Chair/ProjectKinectMagicMirror, accessed May 05, 2013.

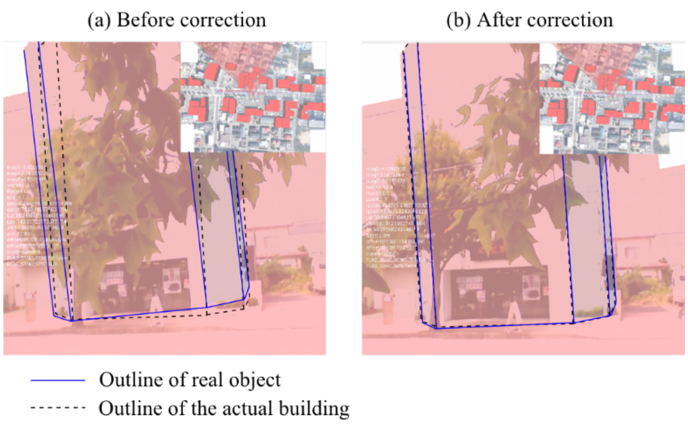


Fig. 9: Correction of camera orientation

Kakuta T., Oishi T., Ono S., Ikeuchi K. (2007). Virtual Asukakyo: A restoration of an archaeological site with mixed reality technology and expansion into a tour guide system. Monthly journal of the Institute of Industrial Science, University of Tokyo, vol. 59, no. 3, 172-175.

Suyang D., Kamat. V. R. (2010). Resolving Incorrect Visual Occlusion in Outdoor Augmented Reality Using TOF Camera and OpenGL Frame Buffer. Proceedings of CONVR2010, 55-63.

Azuma, R. T. (1997). A Survey of Augmented Reality. In Presence: Teleoperators and Virtual Environments 6, 4 (August 1997), 355-385.

Azuma, R.T., Baillot, Y., Behringer, R., Feiner, S., Julier, S., MacIntyre, L. (2001). Recent Advances in Augmented Reality.

7. ACKNOWLEDGEMENT

This research was partially supported by JSPS KAKENHI Grant Number 24560569. The authors sincerely thanks for Dr. Hidekazu Masaki, Mr. Koji Mizukami, and Mr. Kinya Tanaka of KOKUSAI KOGYO Co., Ltd.

NUMERICAL SIMULATION OF WIND LOADS ON HIGH RISE BUILDINGS[1]

Vladimir Alekhin, Aleksey Antipin, Sergey Gorodilov & Sergey Khramtsov
Ural Federal University named after the first President of Russia B.N. Yeltsin, Ekaterinburg, Russia

ABSTRACT: *Article presents a methodology of the numerical simulation of the wind on high-rise buildings, which was developed by the Department of "Computer-aided design of structures" of the Ural Federal University named after the first President of Russia B.N. Yeltsin. Paper includes the results of researches on development of a technique of determination of wind pressure upon high-rise buildings by means of numerical modeling in an ANSYS package. The investigation was carried out within the grant of the Russian Academy of Architecture and Building Sciences. The results are applied to calculation of wind pressure upon a number of high-rise buildings under construction in Yekaterinburg City (Russia).*

Simulation is performed in the program ANSYS. The simulated building is placed in a domain that is the numerical analogue of wind tunnel. Domain sizes are chosen in such a way that simulated buildings do not affect the flow of air on its boundaries. Shear stress transport (SST) turbulence model has been used. This model effectively combines the stability and accuracy to the standard k-ω model in the areas, which are placed near the walls and the effectiveness of the k-e model at a distance from the walls with a smooth transition between them (input expansion functions). For the numerical solution of the governing equations the finite volume method was used (FVM). The scale of the turbulence is assumed to be 200-300m.

Use of the developed technique is shown on the example of calculation of wind pressure and wind velocities in pedestrian area for high-rise building under construction in the City of Ekaterinburg.

KEYWORDS: *high-rise building, wind impact, simulation, wind loads.*

1. INTRODUCTION

Wind loads on high-rise buildings have the great impact on their stress-strain state. Analysis of the standard values of wind pressures for buildings higher than 200 meters shows that the wind pressure can be more dangerous to the overall strength than the nine-point earthquake. Active codes of practice (SNIP 2001, Eurocode 1 1994, British Standard 1995, AIJ Recommendations 1996) do not sufficiently reflect wind effects on high buildings. In order to determine the wind loads both on the facade design and the framework of the building it is necessary to apply the experimental and numerical methods, which include: monitoring and field measurements, wind tunnel tests and numerical simulation.

In the recent 10-15 years computational fluid dynamics (CFD), technology of computations of wind loads on buildings and structures are rapidly developing at a steadily increasing power of computers. The creation of adequate computational models of high-rise buildings providing agreement between the numerical simulation and experimental data gives the possibility of the more accurate estimation of their stress-strain state and more accurate prediction of behavior of structures during their lifetime.

The purpose of the paper is to describe the procedure of determination of wind pressure on the walls and framework of high-rise buildings by numerical simulation. To create a computational model of the numerical analogue of wind tunnel the following steps are required: the choice of a mathematical model of the problem and model of turbulence; creation of the computational domain and finite volume rid; setting the boundary conditions.

2. MATHEMATICAL MODEL

The numerical model of incompressible air flow based on Reynolds equations was used for undertaking of numerical simulations (Loytsyanskiy 2003):

---

[1] Citation: Alekhin, V., Antipin, A., Gorodilov, S. & Khramtsov, S. (2013). Numerical simulation of wind loads on high rise buildings. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

Momentum equation

$$\rho\frac{dV}{dt} = -grad\left(p + \frac{2}{3}\mu_{\Sigma} divV\right) + 2Div(\mu_{\Sigma}\dot{S}) \qquad (1)$$

where ρ – density; V – velocity; p – static pressure; $\mu_{\Sigma} = \mu + \mu_t$, μ – molecular viscosity coefficient, μ_t – turbulence viscosity coefficient; $\dot{S}$ – deformation velocities tensor.

Continuity equation

$$div(V) = 0 \qquad (2)$$

To solve the differential equations the finite volume method is used. Computations are performed using methods and algorithms that are applied in the software package ANSYS. A "hybrid" model of turbulence SST (shear stress transport, transfer of shear stress) is used. The model effectively combines the stability and accuracy of the standard k-ω model in the near-wall regions and the effectiveness of k-ε model away from the wall with a smooth transition between them. This model corresponds to the world experience in solving the similar problems (Menter 2009).

3. THE COMPUTATIONAL MODEL AND BOUNDARY CONDITIONS

The high-rise building and surrounding objects are placed in the domain, which is analogous to a wind tunnel. Domain sizes are selected so that air flow on its boundaries are not affected by buildins placed in it. In the experience of testing in the wind tunnel it is assumed that the building height H affects up to a distance of 10 H. The size of the computational domain in the flow direction should be not less than 5H. The distance behind the building is recommended to be not less than 15 - 20 H. These recommendations correspond to thesis (Dubinsky 2010) and the work on experimental studies (Kozmar 2011, Plate 1982). The minimum sizes of the computational domain are shown in Figure 1 (Dubinsky 2010). The air flow must not be disturbed near the domain boundaries.

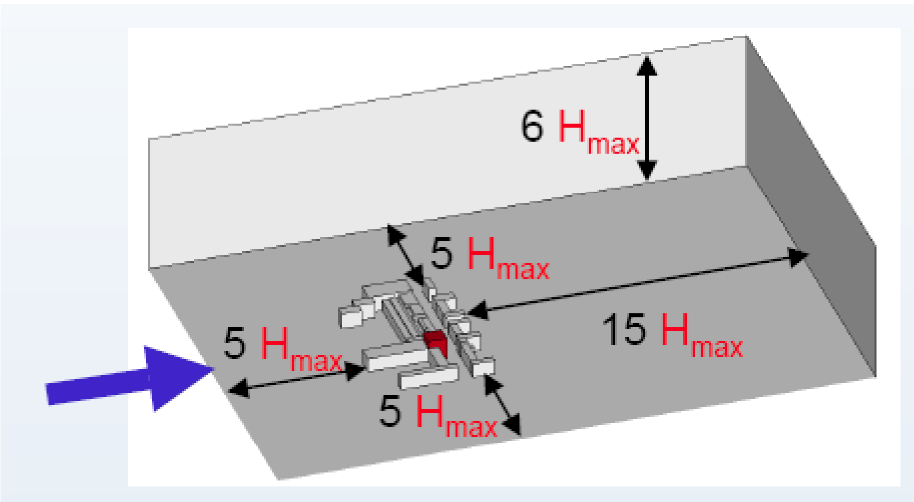


Fig. 1: The minimum dimensions of the computational domain for H-maximum height of the building.

Fig. 2 shows the domain for Iset Tower in which the objects are arranged. The top and side walls of domain are specified as «OPENING» - air flow can pass through the domain wall both inwardly and outwardly. The front of the domain is taken as «INLET» - air flow can be directed only into the domain. The opposite side surface - «OUTLET» - air flow can only be routed from the domain. The bottom surface of the domain and the surfaces of the buildings are taken as «WALL» - zero mass transfer.

The “no slip” condition is used in all boundary walls.

On the bottom boundary of the domain (type WALL) a roughness parameter can be specified which is determined by the characteristic height. This allows taking into account the objects on the ground which is not taken into account in the computational domain geometry (trees, no tall buildings). In urban areas it is recommended to take this option equal to 2 m (Simiu 1984).

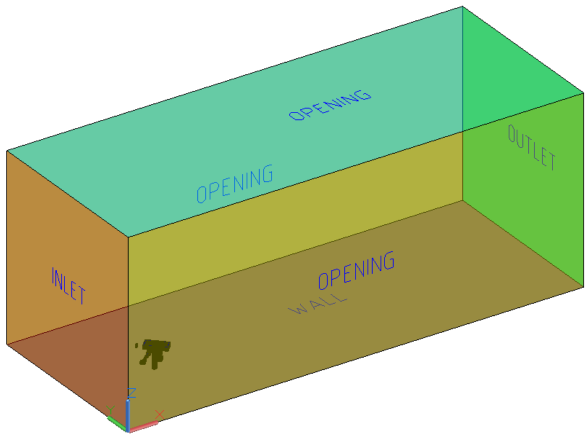


Fig. 2: Scheme of the domain.

On the front surface of the domain «INLET» the distribution of wind velocities on the basis of known meteorological data is given. During the calculation of high-rise buildings in the city of Ekaterinburg city (Russia) the initial distribution of wind speeds is taken as a power law (AIJ 1996):

$$V(z)=V_{ref} \cdot 1.7 \cdot (z / Z_D)^{\alpha}, \qquad (3)$$

where V (z) - wind velocity (m/s) at height z; V_{ref} - wind velocity at a height of 10 m; Z_D - a parameter depending on the height and density of buildings in the surrounding area. For the urban area of Ekaterinburg (V_{ref} = 23 - 13 m/s; α = 0,27; Z_D = 550) the distribution of wind velocities at a height corresponds to the Russian design standards (SNIP 2001).

Temporary law of wind oscillations is taken from (Dubinsky 2010)

$$V = V(z) \cdot (1+0.25 \cdot \sin(\omega \cdot t)), \qquad (4)$$

where the frequency $\omega = 2\pi / 5$, and 5 s - the time of one complete oscillation (obtained on the basis of numerical experiments). Total time for transient calculations was set to 100s, time step was about 1s.

Air parameters used in computations were taken as follows: temperature: 25 º C, the air density: 1.185 kg / m^3; air molar mass: 28.96 kg / kmol. As it was shown by the numerical computations the parameters at heights of buildings about 100 – 200 m varies slightly.

The geometry of the building is modeled precisely and the geometry of other objects included in the domain was modeled coarsely.

As an example the wind loads on 52th floor of the building "Iset Tower" are investigated. Area of high-rise building is 70600 sq.m., height – 209m. It consists of two main blocks: the living part (52 above-ground floors) and underground part (four floors) with parking and technical facilities. "Iset Tower" is a part of new business district "Ekaterinburg - City" that occupies a location in the heart of Ekaterinburg (figure 3).

The area of high-rise buildings is situated close to the river Iset. In the right part of the figure 3 the building of an existing hotel "Hyatt" is shown in the green. On the left side high-rise building complex "Iset Tower" is shown in the yellow. The blue color shows the Iset River. The surface of the circular high-rise building under construction is ribbed (figure 3) and the ribs height is 700mm (figure 4).

Experimental examination in the wind tunnel of the pressure on the building surfaces caused by wind was made by the company «WACKER INGENIEURE», Germany. The scale of the model was 1/380. Due to such a high scale of the model there were some questions about the distribution of wind pressure on the surfaces of the building and the mechanism of their transfer to the ceiling of reinforced concrete frame.

Fig. 3: "Ekaterinburg - City" area (project).

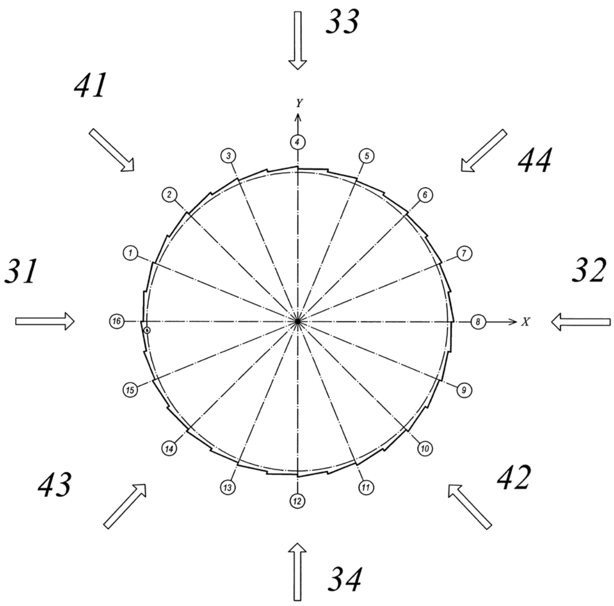


Fig. 4: Shape surface of the circular part of the building. The numbers and arrows show the direction taken in the calculation of the wind. The height of ribs on the facade is 700mm.

Finite volume mesh mostly consisted of the tetrahedral cells with prisms in the wall regions. The size of the cells was assumed to be near the boundaries of the domain - 100 meters, near the surface of the building - 0.5 meters. Figure 5 shows the finite element mesh in the boundary layer.

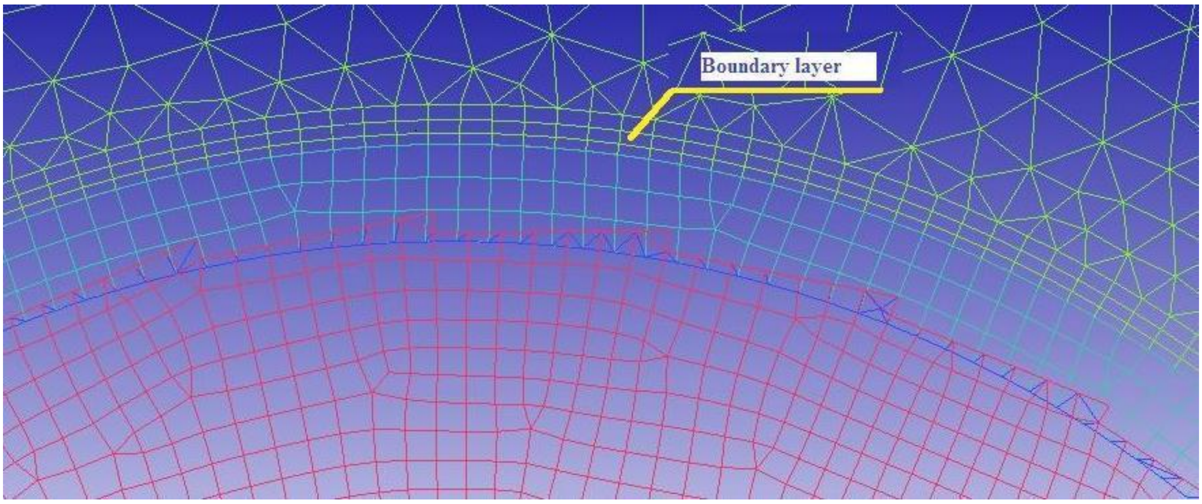


Fig. 5: The boundary layer.

The finite volume mesh size generally requires at least 2-3 finite elements on 1 meter of height. Cells on the surfaces of buildings were chosen mainly square. The triangular cells yield a square, as the square elements gives minimum errors due to averaging. The number and size of cells for the high-rise building satisfies this condition. It can be seen from Figure 6 that in the range of one floor there are 6 finite volumes 0.5 x 0.5 meters. Several theoretical models with different sizes of finite elements were built. In circumstances of the above mentioned recommendations for different grids the same results were obtained.

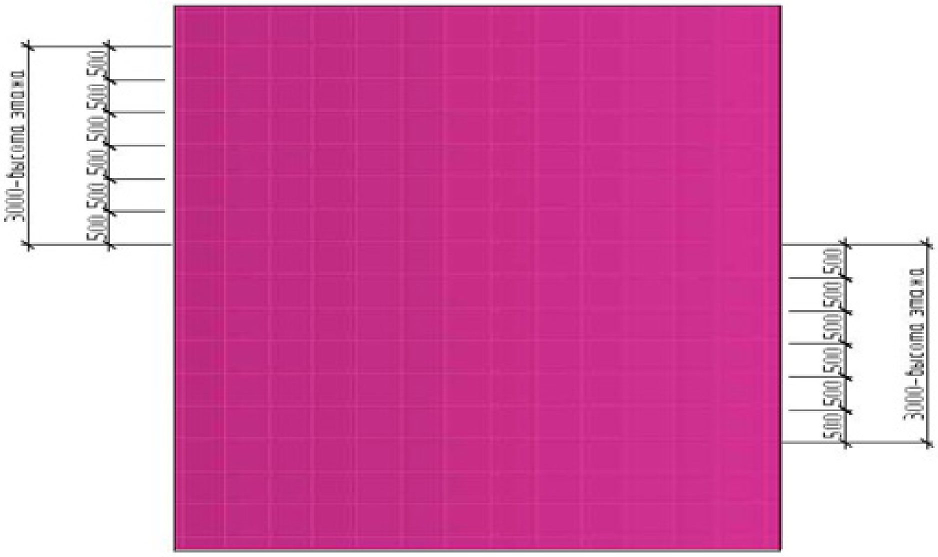


Fig. 6: The part of vertical wall of the building.

4. RESULTS OF COMPUTATIONS

The solution of the steady state problem is done, and the results are clarified by the solution of the trancient problem. Figure 7 shows the characteristic form of pressure distribution along the height of the building. Figure 8 shows the pattern of distribution of velocities at a height of 58.5 m.

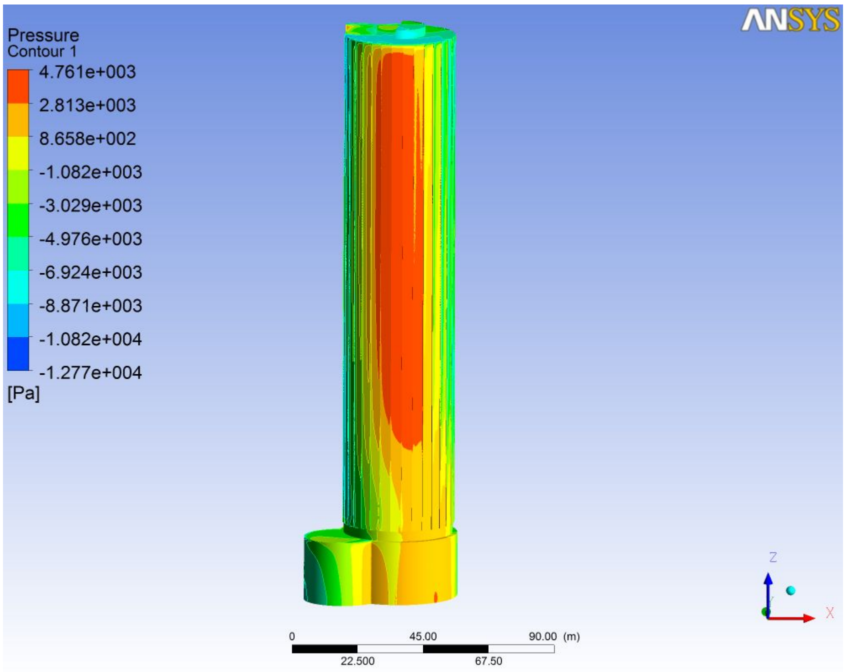


Fig. 7: The distribution of pressure to the building.

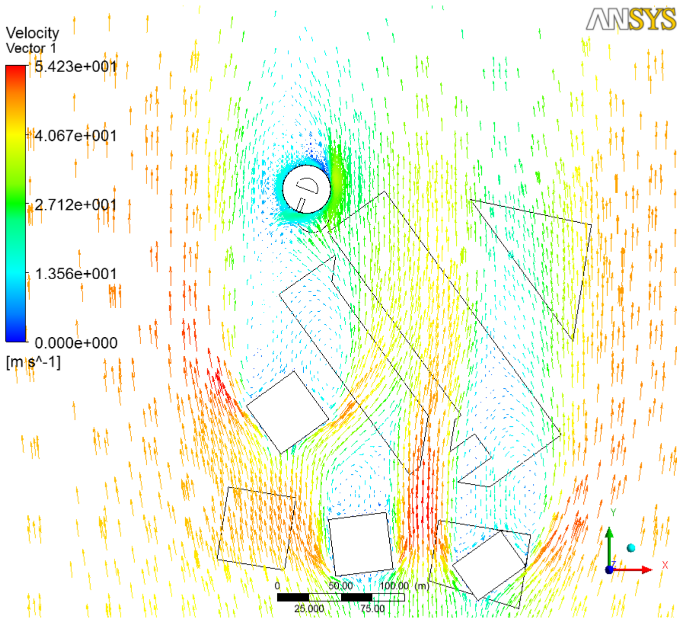


Fig. 8: The distribution of velocities at a height 58.5 m.

The resulting pressure on the surface of the building was transformed with the help of specially designed computer programs to average pressures in the level of floors and was applied to a computational model of the building framework (Figure 9). The development of two computational models of the building was caused by the lack of resources of used computers because automatic transfer of pressure to the computational model of the building is possible only for a solid model using three-dimensional finite elements. The computational model of the framework was created using the core and shell finite elements.

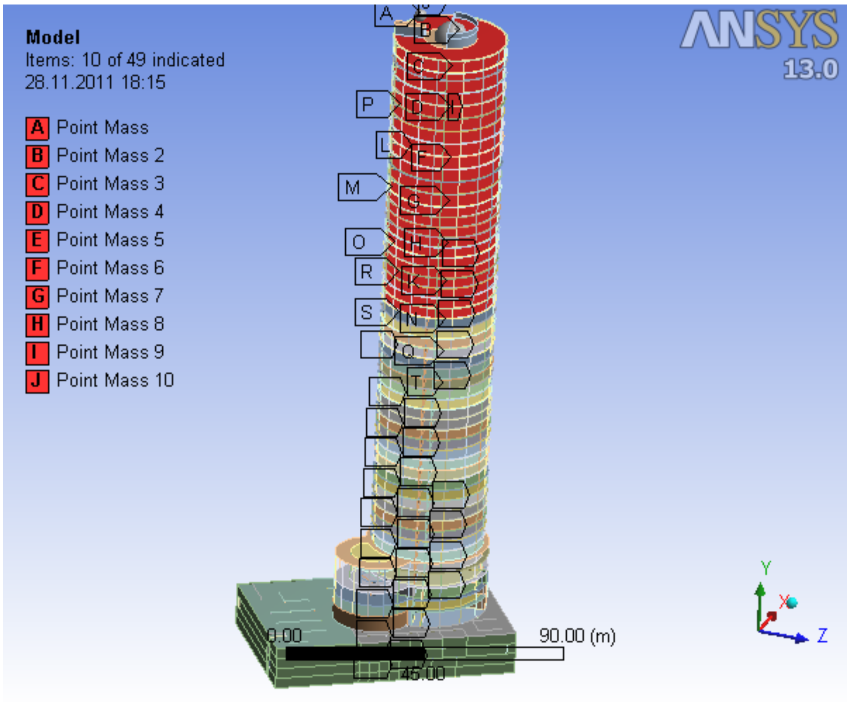


Fig. 9: The computational model of the building framework

Figure 10 shows typical graphs of the mean and fluctuating components of wind pressure in points on the surface of the building.

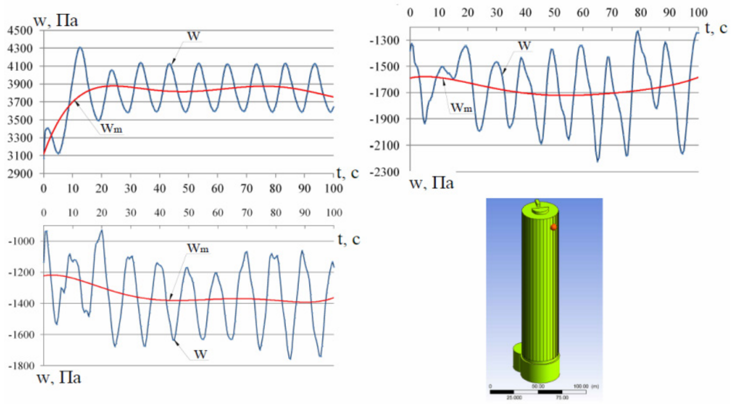


Fig. 10: Graphs of the total wind pressure and the mean component in the point marked in red on the facade of the building.

The obtained results were compared with experimental data: the values of the total force of wind loads acting in the center of gravity of the upper round part of the building.

The numerical method of simulation of aerodynamics of high-rise buildings has been applied to a number of objects under construction and planning in Ekaterinburg (Russia).

The analysis of experience led to a more reasonable calculation in order to determine maximum loads on the structure of buildings. The authors believe that the ultimate test of the correctness of calculations is the coincidence of numerical and experimental data. An experimental model does not fulfill all the requirements of the similarity theory (Plate), and numerical models require experimental verification.

5. CONCLUSION

Numerical analysis showed:

• The numerical estimation of the frequency of natural oscillations of the building design models presented in the paper are quite close to the experimental data.

• The maximum total force of wind loads acting in the center of gravity of the upper round part of the building determined from the simulations for different directions of the wind are close to the experimentally obtained values.

• The difference of values of the wind pressure are due to different structural models of buildings that were used in experimental studies and calculations, as in the numerical analysis the computational model of the building was constructed according to the working draft.

Above considered calculations show qualitative agreement with experimental results.

According to the results of numerical simulation of wind effects it can be concluded that in the design both aerodynamic experiments and numerical analysis are needed. If there is coincidence of experimental and numerical results then they can be used to calculate the skeleton of the building.

6. ACKNOWLEDGEMENTS

Authors thank professors A.S. Noskov and A.V. Khait for important remarks and discussions of research results.

7. REFERENCES

AIJ Recommendations for Loads on Buildings (1996). *Architectural Institute of Japan*, Japan.

British Standard, Loadings for Buildings - Part 2: Code of Practice for Wind Loads (1995). *Building and Civil Engineering Sector Board*, UK.

Dubinsky S.I. (2010). Numerical Modeling of wind effects on tall buildings and complexes (in Russian). PhD Thesis, Russia, Moscow, 231p.

EN 1991-1-4. (1994). Eurocode 1: Basis design and action on structures. Part 1: "Basis design". *CEN*, 232p.

E. J. Plate (1982). Engeneering Metrology, Chapter 13, *Elsevier*, Nertherlands, , p. 573-639.

E. Simiu, R. Skandlan. (1984). The effect of wind on buildings and structures. *Stroyizdat*, Moscow, p.568.

Florian R. Menter (2009). Review of the shear-stress transport turbulence model experience from an industrial perspective, *International Journal of Computational Fluid Dynamics*, Vol. 23, No. 4, p. 305–316.

Hrvoje Kozmar. (2011). Wind-tunnel simulations of the suburban ABL and comparison with international standards. *Wind and Structures*, Vol. 14, No. 1, p. 15-34.

John S. Owenb, Nigel G. Wrightb, Kai Fan Liaw (2007). Fluid–structure interaction of prismatic line-like structures, using LES and block-iterative coupling Dongke Suna, UK.

Loytsyanskiy L.F. (2003). Liquid and gas mechanics. Moscow, Drofa, 840 p.

SNIP 2.01.07-85 (2001). Loads and effects. *State Committee of Russia*. *SUE LAC*, 44 p.

Sridhar Muddada, B.S.V. Patnaik. (2010) An assessment of turbulence models for the prediction of flow past a circular cylinder with momentum injection. *J. Wind Eng. Ind. Aerodyn*, N. 98, p. 575–591.

Wimal Suaris, Peter Irwin (2010) Effect of roof-edge parapet sonmitigating extreme roof suctions, *Wind Eng. Ind. Aerodyn*. N.98, p. 483–491.

Yongchul Kim, JunKanda. (2010)/ Characteristics of aerodynamic forces and pressures on square plan buildings with height variations. J. Wind Eng. Ind. Aerodyn. N. 98, p. 449–465

NUMERICAL SIMULATION AND VISUALIZATION OF AIR FLOW IN RANQUE-HILSCH VORTEX TUBE[1]

Anatoliy Khait, Alexander Noskov, Vladimir Alekhin & Aleksey Antipin
Ural Federal University named after the first President of Russia B.N. Yeltsin, Ekaterinburg, Russia

ABSTRACT: *Visualization of air flow which appears in Ranque-Hilsch vortex tube is performed by numerical simulations using different turbulence models. The following turbulence models have been used during computations: k-ε, k-ε Realizable, k-ε RNG, SST and SAS-SST. It was found out that only SAS-SST turbulence model can predict the existence of large-scale secondary vortex structures within the computational domain. The existence of large-scale secondary vortex structures is confirmed by different experimental studies.*

KEYWORDS: *Ranque-Hilsch effect, vortex tube, computational fluid dynamics, CFD, flow visualization*

1. INTRODUCTION

At present time most buildings are equipped with state-of-the-art climate systems allowing maintenance of optimum values of humidity and air temperature within all rooms. In a winter season these systems carry out heating air in a building and in summertime provide its cooling. The principle of operation of such systems is generally based on thermodynamic cycles of coolants and such systems used to be called chillers. The typical coolants are Freon and Ammonia which are not ecological ones. Chillers also have other essential disadvantages such as design complexity, high labor-output ratio and presence of toxic substances. Nevertheless chillers fill all segments of refrigerating machinery in building area despite its disadvantages.

One of the alternative ways of cooling and heating is use of Ranque-Hilsch vortex tubes. Ranque-Hilsch effect arises in the swirled flows of viscous compressed gas (air in particular) and it works in a special device – vortex tube (Piralishvili et al. 2000; Merkulov 1969). Vortex tubes can use atmosphere air in thermodynamic cycle to produce heat flow. Air also can be used as a heat carrier. Vortex tubes are ecologically effective devices; they have very simple design and structure, low labor-output ratio and some other benefits.

In spite of the benefits of vortex tubes the area of their competitiveness is essentially limited due to low power efficiency. The value of isentropic energy efficiency coefficient (IEEC) calculated by equation (Eq. 1) for modern vortex tubes is not higher than 0,4. If this value increases up to 0,8 vortex tubes will be competitiveness in all building areas.

$$\eta_S = \frac{\Delta I_X}{\Delta I_S} \tag{1}$$

where ΔI_x – difference of enthalpies of inlet and cold flows of vortex tube; ΔI_S – difference of enthalpies in the ideal isentropic gas expansion from the inlet flow pressure to cold flow pressure.

[1] Citation: Khait, A., Noskov, A., Alekhin, V. & Antipin, A. (2013). Numerical simulation and visualization of air flow in Ranque-Hilsch vortex tube. In: N. Dawood and M. Kassem (Eds.), Proceedings of the 13th International Conference on Construction Applications of Virtual Reality, 30-31 October 2013, London, UK.

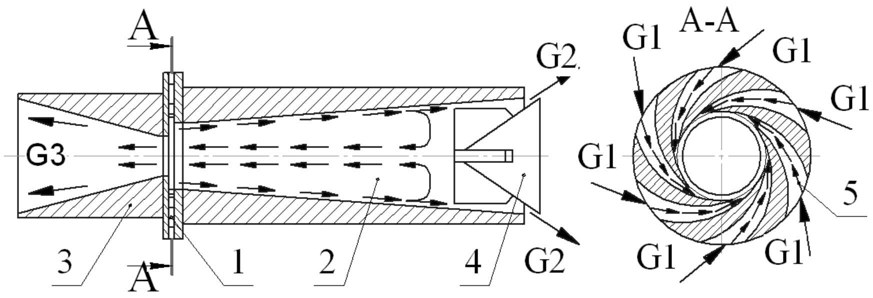


Fig. 1: Schematic diagram of vortex tube. 1- Nozzle inlet; 2 – Vortex energy separation chamber; 3 – Cold flow diffuser; 4 – Hot part cross; 5 –Nozzle duct. G1 – Main compressed gas flow inlet; G2 – Hot flow outlet; G3 – Cold flow outlet

In the simplest case vortex tube is a cylindrical or conical tube which has tangential nozzle inlet for compressed gas (usually air) (fig. 1). Compressed gas is injected into the energy separation chamber passing through the nozzle inlet, and it forms the vortex flow. Outer part (part placed near the wall) of the vortex flow has higher total temperature in compare with inlet gas. Central part of the flow has lower total temperature. Cold and hot gases flow out from different sides of the vortex tube (Piralishvili et al. 2000; Merkulov 1969).

Many researchers (Hilsch 1947; Skye et al. 2006; Selek et al. 2010; Behera et al. 2005; Dincer et al. 2010; Farouk et al. 2007; Dutta et al. 2010; Chang et al. 2011; Lovtsov et al. 2011; Khait et al. 2012) have made different attempts to improve the design of modern vortex tubes in order to increase its IEEC. The conventional approach in the research is to carry out many experimental measurements using large number of various designs and internal structures of vortex tube elements (Hilsch 1947; Selek et al. 2010; Dincer et al. 2010; Chang et al. 2011). In addition many researchers did not make preliminary calculations of vortex tube geometry elements due to complexity of such calculations.

Despite the large number of experimental investigations performed since 1940s when first industrial vortex tube was engineered the energy efficiency of these devices was not change much. It is caused by very complex structure of hydrodynamic processes appearing in vortex flow of compressible gas. An experimental investigation of these processes is also very limited due to low accuracy of existing measuring tools. Up to the present time there is no sufficient theory of energy separation mechanism. Nomination of necessary sizes of industrial vortex tubes is carried out by the empirical dependences received from experimental data of different researches.

In order to understand the main physical principles of Ranque-Hilsch energy separation effect it is necessary to study internal structure of arising vortex gas flow carefully. Carrying out any experimental studies is significantly complicated. It is caused by high velocities of gas and small geometry sizes of a vortex tube. Introduction of any measuring sensors into the vortex tube leads to gas flow distortion. Active using the computer technologies for simulation and visualization of gas flow arising in vortex tubes for the subsequent analysis is caused by such experimental study complexity.

Numerical simulation makes it possible to get preliminary information concerned hydrodynamics of flows appearing in vortex tubes. There are a lot of publications concerned different attempts of 3D vortex gas flow simulation (Skye et al. 2006; Behera et al. 2005; Farouk et al. 2007; Dutta et al. 2010; Lovtsov et al. 2011; Khait et al. 2012). But the practical application of created numerical models for vortex tube elements design optimization can be found not very often (Behera et al. 2005; Khait et al. 2012). First of all to solve this problem we need high performance computers for running numerical simulations. In the second there is some distrust to results of such computations. Many researchers note the existence of divergences between results of numerical computations and experimental measurements.

The turbulence model is a key option in the numerical simulations. Semi empirical turbulence models (k-ε, k-ω, SST etc.) (Wilcox 1994; Ferziger et al. 2002; Menter 2009) give significant divergence during Ranque-Hilsch energy separation effect simulation. For example Skye (Skye et al. 2006) received divergence of the IEEC value about 40 % in compare with experimental data. Farouk (Farouk et al. 2007) used large eddy simulation turbulence model (LES) for simulation of energy separation effect. It was found that application of LES model allows to improve some reliability of data obtained by computations but does not solve the problem completely. Development of turbulence model which allows receiving more adequate structure of vortex gas flow is very important task.

In the paper the visualization of air flow appearing in Ranque-Hilsch vortex tube received by numerical simulations using different turbulence models is presented. The analysis of air flow received by Scale adaptive turbulence model (SAS-SST) (Menter 2009) is performed.

2. NUMERICAL MODEL

The numerical model of gas flow based on Reynolds equations was used for undertaking numerical simulations (Loytsyanskiy 2003):

Momentum equation

$$\rho \frac{dV}{dt} = -grad\left(p + \frac{2}{3}\mu_{\Sigma} divV\right) + 2Div(\mu_{\Sigma} \dot{S}) \tag{2}$$

where ρ – density; V – velocity; p – static pressure; $\mu_{\Sigma} = \mu + \mu_t$, μ – molecular viscosity coefficient, μ_t – turbulence viscosity coefficient; $\dot{S}$ – deformation velocities tensor.

Continuity equation

$$\frac{\partial \rho}{\partial t} + div(\rho V) = 0 \tag{3}$$

Energy conservation equation

$$\frac{\partial}{\partial t}(\rho H) + div(\rho VH) - div\left(\frac{\lambda_t}{c_p} grad(h)\right) = \frac{\partial}{\partial t} p \tag{4}$$

where H – total enthalpy; h – static enthalpy; $\lambda_t / c_p = \mu_t / Pr_t$ – turbulence thermal conductivity coefficient; $Pr_t = 0.8$ – turbulent Prandtl number for air; c_p – heat capacity.

Equation of ideal gas state

$$p = \rho RT \tag{5}$$

where R – gas constant

The following turbulence models have been used during computations: k−ε, k−ε Realizable, k − ε RNG, SST and SAS-SST. The application of more complicated turbulence models including Large Eddy Simulation (LES) and Detached Eddy Simulation (DES) leads to significant increase of computational mesh cells number. Both ANSYS and OpenFOAM have been used to solve numerically the mathematical model equations.

The grid independence study has been performed for both k−ε and SAS-SST turbulence models because these models have fundamental distinctions. It was found out that in the case under consideration grid coarseness do not have strong influence on the value of IEEC (1) if the number of grid cells is higher than 500 000. The finest considered grid was consisted of 2,5 million cells. This observation is in agreement with the results of grid independence study performed by (Dutta et al. 2010). The grid consisting of 750 000 cells was used in further computations.

The wall treatment was performed by wall function method. Such wall treatment can be used for simulation of Ranque-Hilsch energy separation phenomenon because the boundary layers do not have significant influence on energy separation in vortex tube. Energy separation is caused basically by heat exchange between outside layers of the swirled flow moving in the direction of hot flow outlet and central layers moving counter flow in the direction of cold outlet. Dimensionless thickness of the grid boundary layer was in the range of $y^+ = 10 - 200$. This grid resolution can be used in couple with wall function treatment (Menter 2009).

Vortex tube computational domain is depicted in fig. 2. Main geometry sizes of computational vortex tube domain: energy separation chamber diameter D = 16,8 mm; diaphragm diameter d = 9,8 mm; energy separation chamber length and conical angle: L = 168 mm, α = 3,5° (fig. 1).

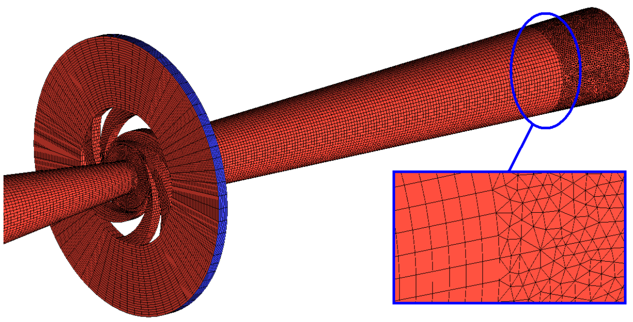


Fig. 2: Vortex tube computational domain

The following initial conditions were used: absolute static pressure p = 10^5 Pa; static temperature T = 300 K; velocities $U_x = U_y = U_z = 0$; turbulence kinetic energy k = 0; turbulence dissipation rate ε = 0. The air was used as a continuum; its properties were accounted for by ideal gas state equation (Eq. 5).

Boundary conditions:

- Vortex tube inlet (flow G1, fig. 1): absolute static pressure p = $5 \cdot 10^5$ Pa; static temperature T = 300 K, turbulence intensity I = 5%.

- Hot flow outlet (G2, рис. 1): absolute static pressure p = $2{,}6 \cdot 10^5$ Pa. The given value of static pressure was chosen in order to obtain the cold mass flow fraction value (Eq. 6) φ = 0,6.

- Cold flow outlet (G3, fig. 1): absolute static pressure p = 10^5 Pa.

- No slip and adiabatic wall boundary conditions were used for all other boundary surfaces.

$$\varphi = G3/G1 \tag{6}$$

where G3 – cold mass flow rate; G1 – inlet mass flow rate.

Computations were carried out in transient formulation. Considered physical time in computations was t = $2 \cdot 10^{-2}$ s. Achievement of a stationary state of the air flow was detected by monitoring of mass flow rate values in all inlets and outlets of the vortex tube computational domain.

The following solver parameters were used:

- Time integration step: adaptive in the range Δt = 10^{-5} - 10^{-7} s.

- Second order scheme for time integration.

- High order scheme for space integration.

3. COMPUTATIONAL INTEGRAL CHARACTERISTICS OF VORTEX TUBE

Performed numerical simulations make it possible to calculate values of IEEC (Eq. 1). Main results of these calculations received using different turbulence models are presented in table 1. It is clear that the most adequate turbulence model showed IEEC value η_S = 0,24. All other turbulence models give very close value of IEEC. At the same time experimental value of this coefficient is about η_S = 0,36 (Lovtsov et al. 2011). This distinction can be caused by inaccuracy of used turbulence models.

Table 1: Isentropic energy efficiency coefficient values for different turbulence models.

No.	Turbulence model	Computational cold mass flow fraction	Cooling degree, $\Delta T = T_{INLET} - T_{COLD}$, K	Isentropic energy efficiency coefficient (IEEC)
1	k - ε	0,59	23,3	0,21
2	k – ε Realizable	0,58	26	0,24

3	k – ε RNG	0,73	24,4	0,22
4	SST	0,58	24,3	0,22
5	SAS-SST	0,64	21,7	0,2

4. VISUALIZATION OF VORTEX AIR FLOW

The visualization of vortex air flow appearing in Ranque-Hilsch vortex tube is made on the basis of results of performed simulations.

4.1 k-ε turbulence model

It was found out that k–ε, k–ε Realizable, k – ε RNG and SST turbulence models predicted very similar flow structure and distribution of main hydrodynamic characteristic within computational domain. That is why the results only for k–ε turbulence model are presented in the paper. Computational distribution of hydrodynamic parameters in the longitudinal vortex tube cross section is presented in fig. 3, 4, 5, 6.

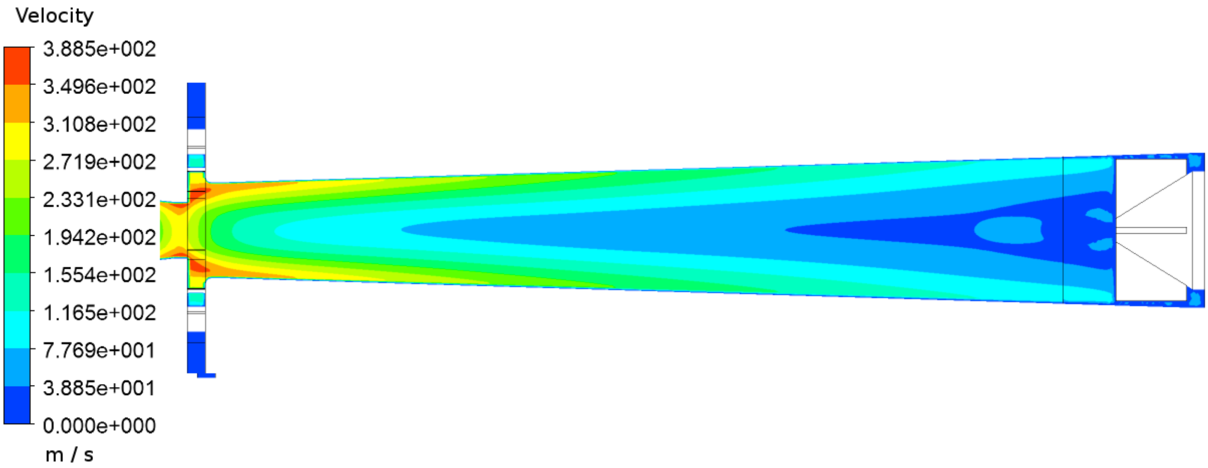


Fig. 3: Distribution of velocity in longitudinal vortex tube cross section

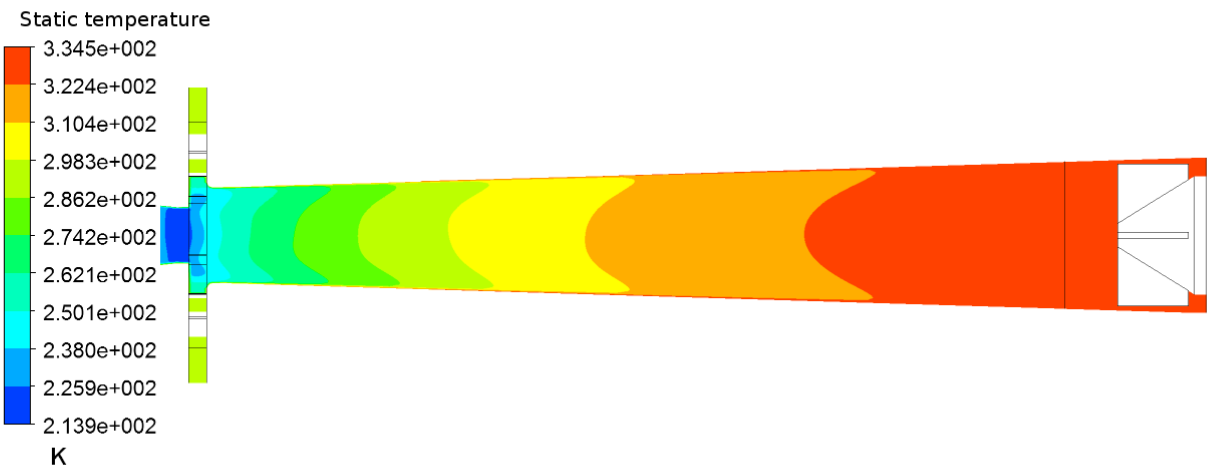


Fig. 4: Distribution of static temperature in longitudinal vortex tube cross section

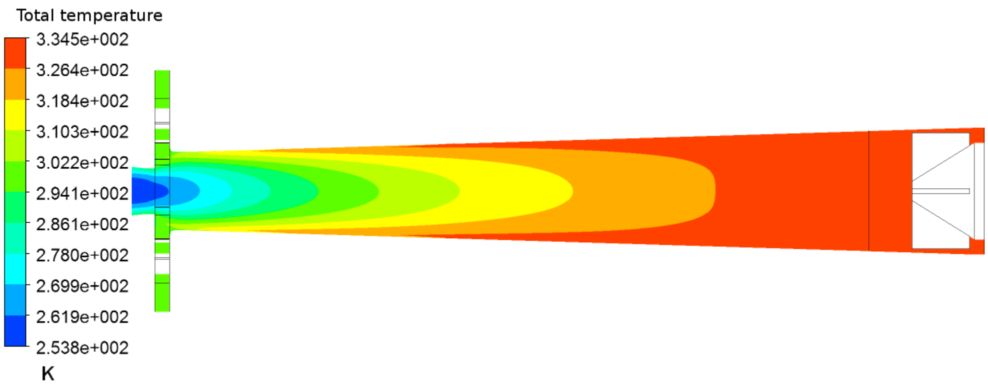


Fig. 5: Distribution of total temperature in longitudinal vortex tube cross section

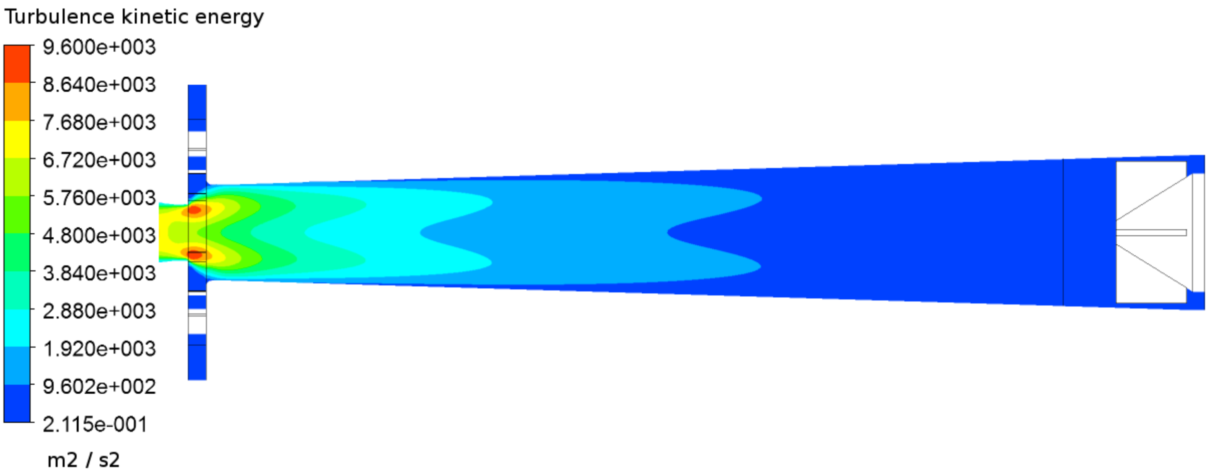


Fig. 6: Distribution of turbulence kinetic energy in longitudinal vortex tube cross section

An analysis of static pressure distribution showed existence of radial pressure gradient which is caused by air flow swirling. Central part of vortex air flow has higher value of static temperature comparing with outer flow part (fig. 4). In the same time total temperature distribution has the opposite tendency (fig. 5). The vortex flow outer part has higher total temperature in compare with the central flow part. This phenomenon can be explained by velocities distribution (fig. 3). The outer part of the vortex flow has the higher value of velocities.

Computational streamlines are presented in fig. 7. The air flow is axisymmetric and stationary.

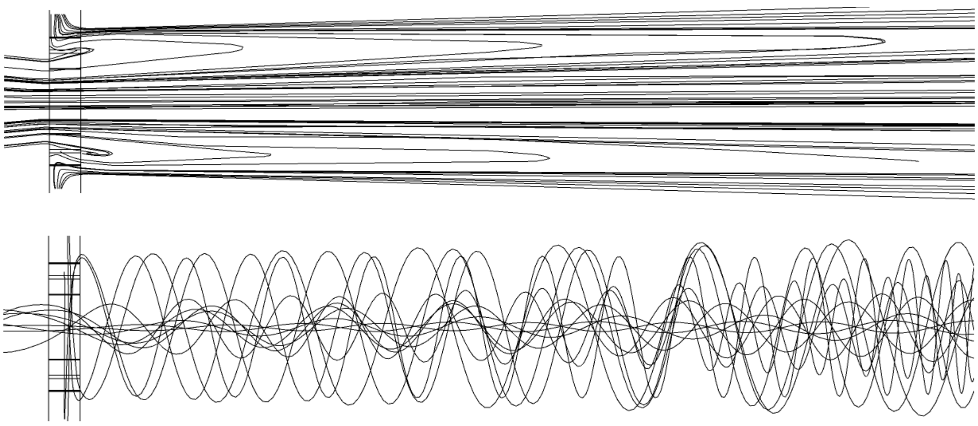


Fig. 7: Computational streamlines in vortex tube found by k-ε turbulence model

4.2 SAS-SST turbulence model

SAS-SST turbulence model shows the structure of appearing vortex flow very different from all other used turbulence models. It can be explained by the fact that this model partially takes into account nonstationarity of turbulence (Menter 2009).

The computational flow structure received by SAS-SST turbulence model shows nonstationary character of the vortex flow. All hydrodynamic parameters undergo continuous pulsation change within the vortex tube computational domain. Distributions of the velocity, static temperature and turbulent kinetic energy in the longitudinal vortex tube cross section are presented in fig. 8, 9 and 10.

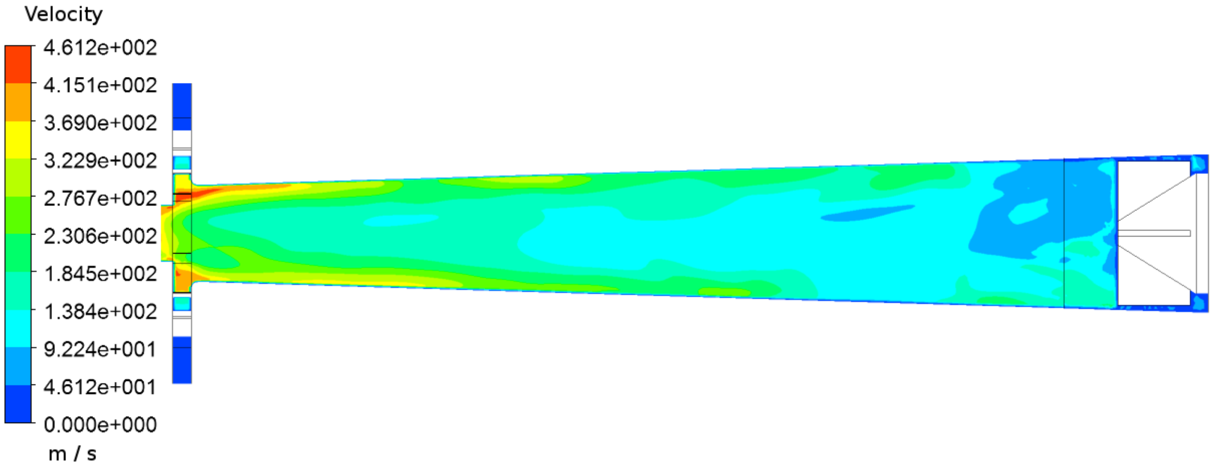


Fig. 8: Distribution of velocity in longitudinal vortex tube cross section

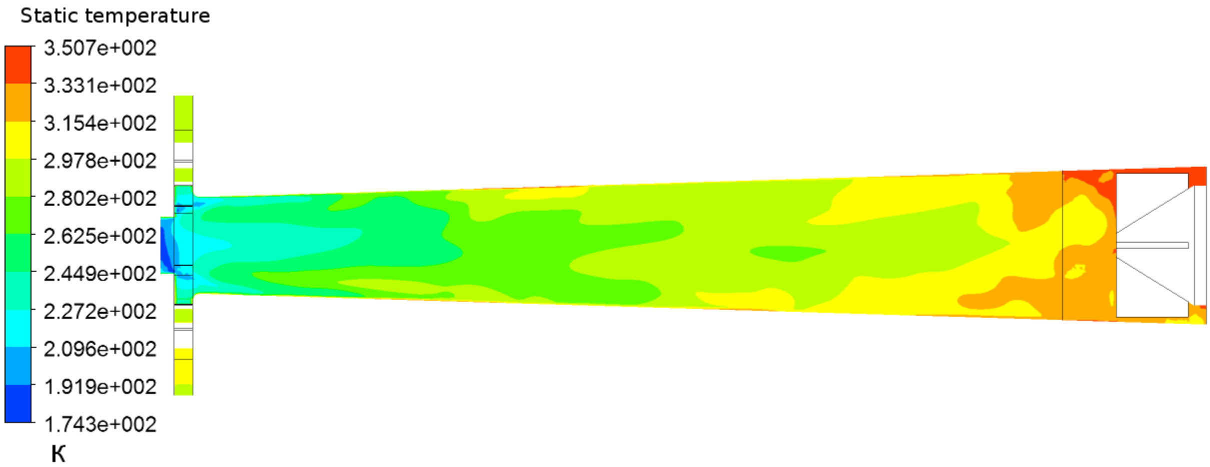


Fig. 9: Distribution of static temperature in longitudinal vortex tube cross section

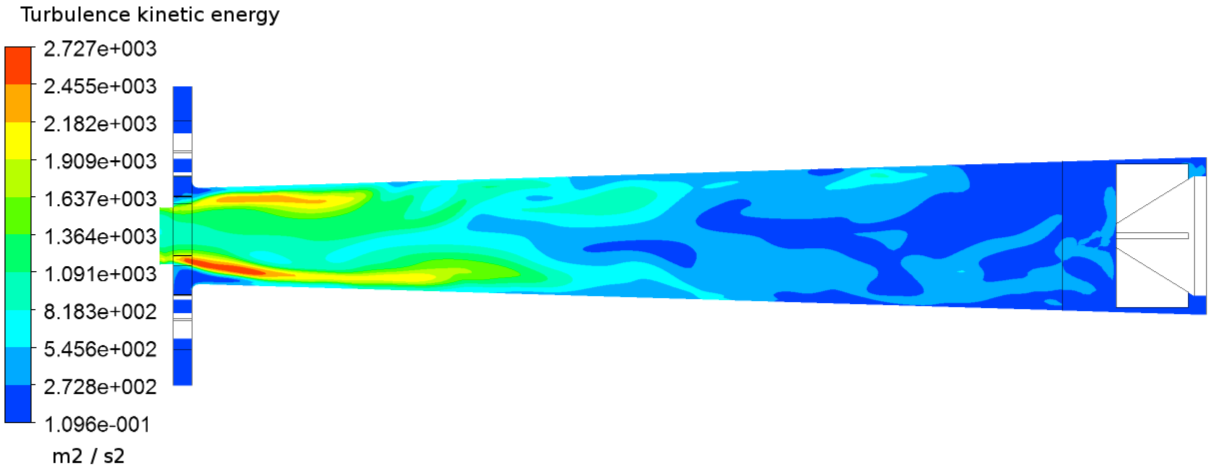


Fig. 10: Distribution of turbulence kinetic energy in longitudinal vortex tube cross section

The flat streamlines within the vortex tube computational domain are presented in fig. 11 in order to visualize the air flow predicted by SAS-SST turbulence model. Unlike a case of application of standard k−ε turbulence model the resulted vortex flow is asymmetric. Also there is a precession of central flow part.

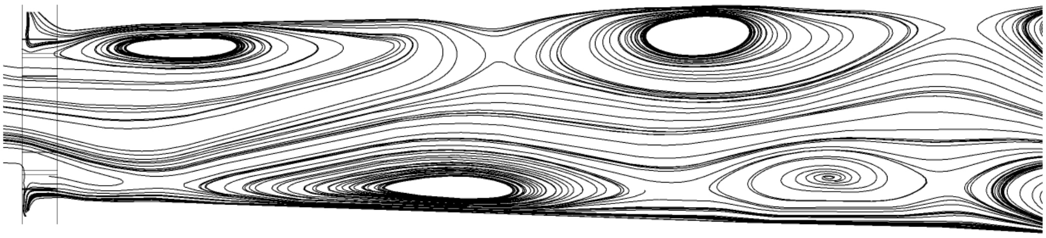


Fig. 11: Flat computational streamlines in vortex tube found by SAS-SST turbulence model

Presented flow visualization makes it possible to find out the existence of vortex structures between central and outer flows. All other used turbulence models do not predict these vortex structures. In the case of application of SAS-SST turbulence model vortex structures fill the entire vortex tube energy separation chamber. In 3D visualization these structures compose continues large-scale secondary vortexes. The existence of such vortexes has been found in some experimental visualization.

Arbuzov (Arbuzov et al. 1997) experimentally study the air vortex flow in square channel where the Ranque-Hilsch effect arises. The method of optical density phase field visualization has been used. The real time visualization of vortex flow has been made using this optical method. Minimum exposition time was 250 ms. Existence of two large-scale secondary vortex structures was found out (fig. 12).

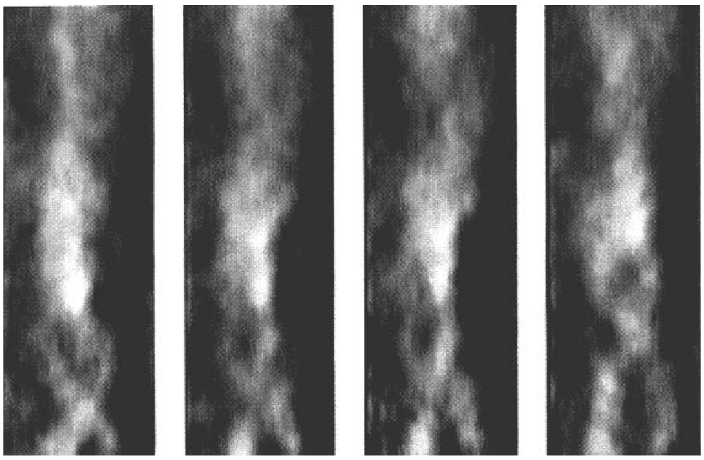


Fig. 12: Experimental large-scale secondary vortex structures optical visualization (Arbuzov et al. 1997)

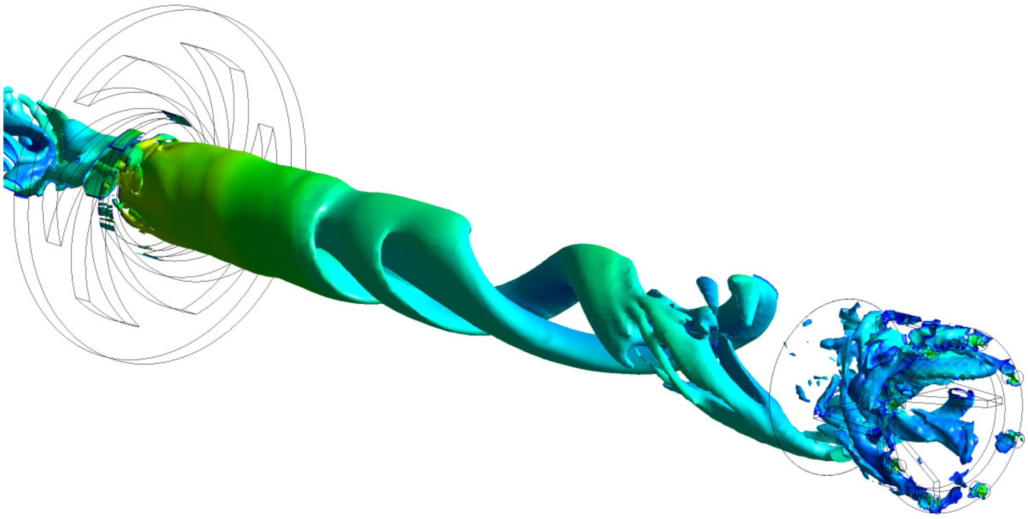


Fig. 13: 3D visualization of large-scale secondary vortex structures in vortex tube received by SAS-SST turbulence model and “vortex core region” algorithm (stream surfaces)

The “vortex core region” algorithm of ANSYS was used to visualize large-scale secondary vortex structures (fig. 13). Three dimensional streamlines are presented in fig. 14. The visualization has very close qualitative agreement with experimental results presented in fig. 12. As a result of visualization we can conclude that SAS-SST turbulence model makes it possible to predict vortex flow structure more precisely unlike other above observed semi empirical turbulence models (k-ε, SST etc.).

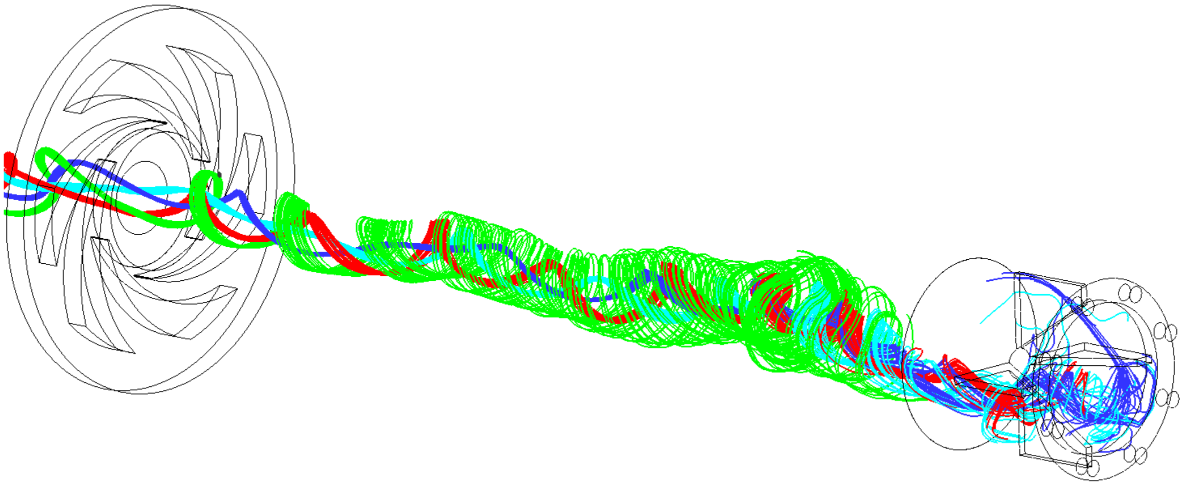


Fig. 14: 3D streamlines in vortex tube received by SAS-SST turbulence model.

5. CONCLUSION

Analysis of vortex tube integral characteristics shows that the isentropic energy efficiency coefficient (IEEC) has the same value for all turbulence models which were under consideration in the paper. The most adequate turbulence model shows IEEC value $\eta_S = 0,24$. The experimental value of this coefficient is about $\eta_S = 0,36$. This distinction can be caused by inaccuracy of turbulence models. The SAS-SST turbulence model does not increase the accuracy of IEEC prediction but makes it possible to get much more accurate internal structure of appearing vortex air flow.

The visualization of internal structure of appearing vortex flow showed that k−ε, k−ε Realizable, k − ε RNG and SST turbulence models predict very similar flow structure. At the same time SAS-SST turbulence model shows the structure of vortex flow very different from all other used turbulence models. It can be explained by the fact that this model partially takes into account nonstationarity of turbulence. Only SAS-SST turbulence model predict the existence of large-scale secondary vortex structures within the computational domain. The existence of such vortex structures is confirmed by different experimental studies.

SAS-SST turbulence model can be recommended for further simulations intended for vortex tube energy efficiency improvement because this model allows more accurate prediction of the vortex air flow. If the vortex tube energy efficiency increases up to corresponding values then this device will be competitive in all building and construction areas.

6. ACKNOWLEDGEMENTS

Authors thank A.V. Lovtsov for important remarks and discussions of research results. Partial financial support of presented study by Ural Research and Design Institute of Russian Academy of Architecture and Construction Sciences is gratefully acknowledged.

7. REFERENCES

Arbuzov V. A., Dubnischev Yu. N., Lebedev A. V., Pravdina M. H. and Yarovskiy N. I. (1997). Observation of large-scale hydrodynamic structures in vortex tube and Ranque effect, *JTF letters*, Vol. 23, No. 23, 84-90.

Behera U., Paul P. J., Kasthurirengan S., Karunanithi R., Ram S. N., Dinesh K. and Jacob S. (2005). CFD analysis and experimental investigations towards optimizing the parameters of Ranque–Hilsch vortex tube, *International journal of heat and mass transfer*, No. 48, 1961-1973.

Chang K., Li Q. and Zhou G. (2011). Experimental investigation of vortex tube refrigerator with a divergent hot tube, *International journal of refrigeration*, No. 34, 322-327.

Dincer K., Avci A., Baskaya S. and Berber A. (2010). Experimental investigation and energy analysis of the performance of a counter flow Ranque-Hilsch vortex tube with regard to nozzle cross-section areas, *International journal of refrigeration*, No. 33, 954-962.

Dutta T., Sinhamahapatra K. P. and Bandyopdhyay S. S. (2010). Comparison of different turbulence models in predicting the temperature separation in a Ranque–Hilsch vortex tube, *International journal of refrigeration*, No. 33, 783-792.

Farouk T. and Farouk B. (2007). Large eddy simulations of the flow field and temperature separation in the Ranque–Hilsch vortex tube, *International journal of heat and mass transfer*, No. 50, 4724–4735.

Ferziger J. H. and Peric M. (2002). Computational methods for fluid dynamics, 3rd edition, *Springer*, 423.

Hilsch R. (1947). The use of expansion of gases in a centrifugal field as a cooling process, *Rev. Sci. Instrum.*, No. 18(2), 108-113.

Khait A., Noskov A., Alekhin V. and Lovtsov A. (2012). Mathematical simulation of Ranque-Hilsch vortex tube heat and power performances, *Proceedings of 14th International conference on computing in civil and building engineering*, Moscow, 160-161.

Lovtsov A. V., Noskov A. S. and Khait A. V. (2011). Optimization of vortex forming device used in Ranque-Hilsch vortex tubes, *Proceedings of 4th international conference on Heat and mass transfer and hydrodynamics in swirling flows*, Moscow Power Engineering Institute, 282-283.

Loytsyanskiy L. F. (2003). Liquid and gas mechanics, *Moscow, Drofa*, 840.

Menter F. R. (2009). Review of the shear-stress transport turbulence model experience from an industrial perspective, *International journal of computational fluid dynamics*, Vol. 23, No. 4, 305-316.

Merkulov A. P. (1969). Vortex effect and its application in technique, *Moscow, Mechanical engineering*, 184.

Piralishvili Sh. A., Polyaev V. M. and Sergeev M. N. (2000). Vortex effect. Experiment, theory, technical solutions, *Moscow, Energomash*, 415.

Selek M., Tasdemir S., Dincer K. and Baskaya S. (2010). Experimental examination of the cooling performance of Ranque-Hilsch vortex tube on the cutting tool nose point of the turret lathe through infrared thermography method, *International journal of refrigeration*, doi:10.1016/j.ijrefrig.2010.11.008, 1-9.

Skye H. M., Nellis G. F. and Klein S. A. (2006). Comparison of CFD analysis to empirical data in a commercial vortex tube, *International journal of refrigeration*, No. 29, 71–80.

Wilcox D. C. (1994). Turbulence modeling for CFD, *DCW industries Inc.*, California, 560.